Introduction

MR-linac devices that combine magnetic resonance imaging (MRI) and a linear accelerator (linac) are currently being developed with the aim of integrating the advantages of MRI into linac-based radiotherapy (RT) and enabling online adaptive MRI-guided RT (MRgRT) (Raaymakers et al 2009, Fallone 2014, Keall et al 2014). The potential advantages of MRgRT over conventional image-guided radiotherapy when using (for example) cone beam computed tomography (CBCT) devices are its high soft tissue contrast (McPartlin et al 2016), its functional imaging capabilities and the absence of radiation exposure to the patient. A recent study has already concluded that the MR-linac technology is viable for clinical trials at large comprehensive cancer centers (Sanderson et al 2017). Despite the benefits from a medical point of view, some basic dosimetric problems persist in MRgRT.

In the presence of magnetic fields (as they occur in the MRI component of an MR-linac), the trajectories of charged particles are influenced by the Lorentz force. This effect changes the dose deposition by secondary electrons in high-energy photon beams, especially if combinations of media such as air and water are involved. In this case, the mean free path length of secondary electrons is longer in air than in water (Raaijmakers et al 2005). This effect has a direct impact on reference dosimetry, where air-filled ionization chambers inside water phantoms are commonly used. The impact of an external magnetic field on dose measurements using ionization chambers was investigated previously in several studies (Meijsing et al 2009, Reynolds et al 2013, Smit et al 2013, O’Brien 2016, Malkov and Rogers 2017, Spindeldreier...
et al 2017). All groups observed a change in the response of the ionization chamber that can be taken into account by a correction factor $k_B$.

This work systematically investigates the responses of eight commercially available ionization chambers in setups that are not created for experimental validation, but that are based on the general recommendations for reference dosimetry as recommended in current dosimetry protocols such as TRS 398 (Andreo et al 2006) and DIN 6800-2 (Deutsches Institut für Normung 2008). We assume that an optimal setup includes a water phantom with a minimum size of $30 \times 30 \times 20 \text{ cm}^3$, a photon beam with a field size of $10 \times 10 \text{ cm}^2$ at the phantom surface and a magnetic field that is constant over the whole phantom. We validated our results in an experiment in which we set the experimental conditions to be as close as possible to the optimal setup, which is also suitable for measurement in MR-linac systems (ViewRay MRIdian, ViewRay Inc, Cleveland, United States, 0.35 T/6 MV and Elekta Unity, Elekta AB, Stockholm, Sweden, 1.5 T/7 MV).

**Materials and methods**

**Simulation software and parameters**

Calculations for this study were performed using EGSnrc (Kawrakow et al 2017), with the following parameters: ESTEPE = 0.01, EM ESTEPE = 0.02, ECUT = 0.521, PCUT = 0.001.

All simulations were performed with the ‘egs_chamber’ user code published by Wulff et al (2008b).

Variance reduction was applied in the form of photon cross-section enhancement (XCSE) and intermediate phase-space scoring (IPSS) as described earlier by Wulff et al (2008b). The simulated chambers were surrounded by a cube for IPSS. Inside the cube, XCSE was used with a XCSE factor of 512.

Magnetic fields were included in the ‘egs_chamber’ user code using the new, enhanced algorithm for electron transport in electromagnetic fields (EEMF) that was recently published by Malkov and Rogers (2016).

**Orientation**

Multiple setups of hybrid MR-linacs with different orientations of the magnetic field with respect to the radiation beam have been proposed recently (Raaymakers et al 2009, Fallone 2014, Keall et al 2014). The first clinically available MRgRT systems (Dempsey et al 2006, Raaymakers et al 2009) were constructed with an orthogonal orientation of the photon beam and the magnetic field.

Generally, for accurate dose measurements, the axis of a thimble-type chamber should be perpendicular to the beam, whereas the axis of a plane-parallel chamber should be parallel to the beam. Consequently, there is only one possible orientation with respect to the magnetic field direction for a plane-parallel chamber and one free angle of orientation for a thimble-type chamber. In this work, the angle between the magnetic field axis and the chamber axis is denoted by $\alpha$ (see figure 1).

For measurement, a setup that is easy to establish is preferable (i.e. one where the magnetic field is parallel ($\alpha = 0$ or 180°) or orthogonal ($\alpha = 90$ or 270°) to the chamber axis). For our work, we decided to use orientations of 180° and 90°. Recent publications have shown that these orientations should not be affected by any dead volume effects for magnetic flux densities of 0.35 and 1.5 T (Malkov and Rogers 2017, Spindeldreier et al 2017).

**Accelerator and beam models**

To model the accelerator, we used a full Monte Carlo simulation of a commercial Elekta 6 MV FFF linac created in BEAMnrc, as well as a published photon spectrum of the Elekta Unity MR-linac (Ahmad et al 2016). Such energy distributions can also be used as an input for egs_chamber.

Two different approaches were considered. In the first approach, the full BEAMnrc model of the Elekta 6 MV FFF accelerator was directly coupled via a shared library to the egs_chamber user code, as described by Tonkopi et al (2005). This method allows efficient calculations to be made on high-performance computer clusters without generating excessively large data files. For the second approach, only a rectangular $10 \times 10 \text{ cm}^2$ photon beam was modeled instead of the full accelerator. For this, photons were randomly drawn from the 7 MV spectrum.

**Simulated ionization chambers**

A list of all simulated ionization chambers together with some characteristic data is given in table 1.

Except for the PTW 30013 ionization chamber, all chamber geometries and material information have been used in previous publications (Ubrich et al 2008, Wulff et al 2008a, Zink and Wulff 2008). Simulation of the PTW 30013 ionization chamber was based on plans provided by PTW as well as on a microCT scan carried out to clarify the chamber’s geometry using a the cone-beam CT system of a small animal image-guided radiotherapy system (SAIGRT, OncoRay, Dresden, Germany) (Tillner et al 2016).
Determination of correction factors

The effects of the magnetic field on ionization chamber readings are twofold. On the one hand, the dose profile of a photon beam is influenced by the magnetic field at the lateral edges (lateral dose shift) and the depth dose decreases even if the ionization chamber is not part of the experimental setup. For small fields, this phenomenon may considerably influence the dose deposited in the measurement volume. On the other hand, the response of the ionization chamber is altered by the magnetic field presence. A correction factor for a specific ionization chamber should only include the latter effect; however, as a basic principle, a combination of the two effects is always observed in simulations as well as in measurements. In order to take this into account, we simulated the change of the dose at the reference point in a cylinder with a radius of 1 cm and a height of 0.2 cm ($D_{w,B}$). Later, the total change of dose inside the ionization chambers in the presence of a B-field ($D_{ch,B}$) was divided by the relative change of dose caused by the lateral and depth shift of the dose profile to calculate the actual correction factor $k_B$ (O’Brien 2016):

$$k_B = \frac{D_{ch}}{D_{w,B}} \times \frac{D_{w,B}}{D_w}.$$

For the calculation of correction factors by Monte-Carlo simulation, reference points of all chambers were placed at a depth of 10 cm inside a 30 × 30 × 20 cm³ water phantom. The source-detector distance was 143.5 cm for the Elekta Unity and 90 cm for the MRIdian. The photons striking the phantom were sampled from the 7 MV spectrum for the Elekta Unity simulation and from the 6 MV FFF full accelerator simulation for the MRIdian.

All errors reported are for a 95% confidence interval and were calculated based on the variance of the Monte Carlo simulation.

Experimental validation of the simulation method

For experimental validation of the simulation results, measurements were performed in a water phantom using a 6 MV linear accelerator (Elekta Precise Treatment System, Elekta AB, Stockholm, Sweden) in combination with an electromagnet (Bruker ER07, Ettlingen, Germany). The PTW 30013 ionization chamber was mounted at a 10 cm water equivalent depth inside a 21 × 7 × 21 cm³ water phantom. The phantom was placed between

| Name     | Manufacturer | Type       | Sensitive volume [mm³] |
|----------|--------------|------------|------------------------|
| Roos     | PTW          | Plane-parallel | 0.39                   |
| NACP-02  | Scanditronix | Plane-parallel | 0.16                   |
| Adv. Markus | PTW        | Plane-parallel | 0.02                   |
| Markus   | PTW          | Plane-parallel | 0.057                  |
| PTW30015 | PTW          | Rigid      | 1                      |
| PTW30016 | PTW          | Rigid      | 0.3                    |
| NE2571   | Phoenix dosimetry | Farmer  | 0.69                    |
| PTW30013 | PTW          | Farmer     | 0.6                    |

Table 1. List of the simulated ionization chambers.

Figure 1. Definition of the angle $\alpha$. Experiments showed that the response of a Farmer-type ionization chamber greatly depends on the angle between the chamber axis and the magnetic field axis (Smit et al 2013).
the pole shoes of the magnet with a maximum magnetic flux density of 1.45 T at an SSD of 110 cm. The monitor chamber was calibrated in this setup and 100 MU were applied in the following measurements using a $5 \times 10$ cm$^2$ photon field.

The measurements were performed on three consecutive days. The phantom was permanently positioned between the pole shoes, but the ionization chamber was inserted and repositioned every day (i.e. for each measurement). The chamber orientations chosen—$\alpha = 90^\circ$ and $\alpha = 270^\circ$—were realized by switching the magnetic field direction.

The magnetic flux density was monitored using a Hall effect sensor that was placed directly on one of the pole shoes and was adjusted with an accuracy of $\pm 1$ mT.

Errors (95% confidence interval) were calculated from the standard error of the mean and from an additional absolute uncertainty of $\pm 0.3\%$ accounting for fluctuations observed in the signal of the linac monitor chamber.

For benchmarking our simulation method, this experimental setup including the PTW 30013 ionization chamber was modeled in EGSnrc. A flattening filter was added to the 6 MV full accelerator simulation to align it with the experimental conditions. This simulation setup was also used for an additional calculation that was aiming for reproducing previously published results for an ionization chamber of type NE2571 placed inside a PMMA phantom (Smit et al 2013).

In order to be able to directly compare the simulations with experimental results, the change of the detector signal ($\frac{D_{ch}}{D_{ch,B}}$) instead of the correction factor $k_B$ was calculated, because this can be obtained directly by measurement without the need for additional calculations or theoretical assumptions regarding the lateral and depth shift of the dose profile.

Results

The correction factors for the Elekta Unity MR-linac (7 MV) are given in table 2 for both chamber orientations. For this magnetic flux density, the highest correction was calculated for the plane-parallel Roos chamber, where the calculated dose increased by 7.9(2)%. The highest impact on the thimble-type chambers for the 1.5 T MR-linac system was calculated for the PTW 30013, where the simulated signal increased by 4.9(2)% for a perpendicular orientation. In a parallel orientation, only small corrections were found for thimble-type chambers, where the change of signal never surpassed 0.8(2)% (PTW 30015).

Table 2 also shows correction factors for the ViewRay 6 MV system. While the correction factors are similar for thimble-type ionization chambers, there are some differences for the Roos and NACP-02 plane-parallel chambers, where the response is influenced less at this magnetic flux density.

In figure 2, the influence of the magnetic field on the detector response is shown for magnetic flux densities ranging from 0 to 2.5 T.

Magnetic flux densities higher than 2 T can result in an inverse effect in which the response of the ionization chamber decreases instead of increasing. This effect was most dominant for the PTW 30015 in perpendicular orientation, where the scored dose decreased by 3.3(1)%% at 2.5 T.

Overall, the maximum effect of a magnetic field on radiation dose measurements with ionization chambers was observed at a magnetic flux density of approximately 1 T. For higher and lower magnetic flux densities, the effect decreases similarly. All simulated thimble-type chambers showed a similar change in response, while there were larger differences for plane-parallel chambers.

The results of the benchmark experiment are presented in figure 3. In this experiment, the highest absolute standard error of the mean was $\pm 0.34\%$ at 1.425 T for $\alpha = 90^\circ$. By comparison, the lowest absolute standard error of the mean was calculated for the same orientation, but at 0.875 T, where it was $\pm 0.05\%$.

For direct comparison of the simulation results with the benchmark experiment, the root-mean-square deviation (RMSD) between the measurement and the simulation was calculated. Overall, a good agreement between the measurement and the simulation was observed, as illustrated by the total RMSD of 0.44%.

Discussion

In the study presented in this paper, a systematic MC simulation of correction factors for ionization chambers used for reference dosimetry was performed in a representative experimental setting for a variety of chambers and a wide range of magnetic flux densities.

We utilized the Monte Carlo package EGSnrc because it has a long history of optimization for ionization chamber simulations (Rogers 2006) and because it is considered to be a kind of ‘gold standard’ in medical physics.
We also included plane parallel ionization chambers because, in the future, they may become suitable for reference dosimetry, as seen in DIN 6800-2 (Deutsches Institut für Normung 2008).

When thimble-type chambers were oriented in such a way that they were perpendicular to the magnetic field, they showed a change in response comparable to that of plane-parallel chambers. By contrast, only a small impact of the magnetic field was observed when the magnetic field was parallel to the chamber’s axis.

At a magnetic flux density of approximately 1 T, the maximum effect of the magnetic field on the response of all the ionization chamber types investigated was observed. The peak of this effect at 1 T might potentially be explained by the trajectories of the secondary electrons. We hypothesize that, at this magnetic flux density, the trajectories may be bent to form a path that aligns with the dilatation of the sensitive volume; thus, for this situation, the probability of presence for an electron is greatest inside the sensitive volume. Hence, the maximum deposited dose is reached at this magnetic flux density as well. For higher magnetic flux densities, the trajectories are bent even more and the secondary electrons leave the chamber again, thus leading to a decrease in the deposited dose. This effect has only a minor influence on thimble-type chambers in parallel orientations, as the

| Orientation α | 0.35 T (6 MV) | 1.5 T (7 MV) |
|---------------|--------------|--------------|
| Roos          | —            | 0.9689(10)   | 0.9272(12)   |
| NACP-02       | —            | 0.9765(13)   | 0.9372(14)   |
| Adv. Markus   | —            | 0.9903(14)   | 0.9720(15)   |
| Markus        | —            | 0.9920(14)   | 0.9809(15)   |
| PTW30016      | 180°         | 0.9977(18)   | 0.9931(17)   |
| PTW30015      | 180°         | 0.9980(14)   | 0.9929(16)   |
| NE2571        | 180°         | 0.9995(12)   | 0.9963(16)   |
| PTW30013      | 180°         | 0.9976(16)   | 0.9963(16)   |
| PTW30016      | 90°          | 0.9770(18)   | 0.9534(14)   |
| PTW30015      | 90°          | 0.9694(14)   | 0.9798(14)   |
| NE2571        | 90°          | 0.9700(12)   | 0.9638(14)   |
| PTW30013      | 90°          | 0.9684(16)   | 0.9535(14)   |

Figure 2. Change in detector response for $\alpha = 180°$ (top) and $\alpha = 90°$ (bottom), as defined in figure 1. All values were calculated using the Elekta Unity photon spectrum.
broadening of the sensitive volume does not match the direction in which the electrons are bent. These effects have been illustrated by Meijsing et al (2009).

Our simulations do not include any modification of chamber models to account for recently proposed dead volume effects (Spindeldreier et al 2017), but correction factors are presented for a setup where these effects are negligible. This assumption is confirmed by the calculated results.

Our simulated Elekta 7 MV correction factors for the PTW30013 and NE2571 ionization chambers are comparable to published values (O’Brien 2016). For parallel orientations, the results match in a 3-sigma error interval. There are differences for the orthogonal orientation, where we calculated corrections that differ by 1% and 2.5% for the NE 2571 and the PTW 30013 Farmer ionization chambers from the values given by O’Brien et al (2016).

Our simulated correction factors for the PTW 30013 in an Elekta Unity setup are very close to recently published results (Spindeldreier et al 2017), despite we used a MR-linac spectrum instead of an 6 MV spectrum as well as we did not adjust for any dead volume effects.

Corrections given for the ViewRay System can also be compared for the PTW30013 with the results published by Spindeldreier et al (2017); and confirm these in a single error interval.

In the benchmark experiment, we observed considerable fluctuations between the day-to-day measurements, especially for high magnetic flux densities. Currently, the reason for this is unknown. For better benchmarking, more measurements must be considered.

Within the estimated confidence intervals, the simulations fit the results of the benchmark experiment, but differences appear with increasing magnetic flux density. This may be caused by a small misalignment of the magnetic field axis and the ionization chamber axis. It has been shown that a tilt of the magnetic field by only 3° can decrease the measured dose by roughly 1% at 1.5 T, while the influence is negligible for magnetic flux densities below 0.6 T (Malkov and Rogers 2016).

In view of this, MR-linac systems that apply strong magnetic fields must ensure a highly accurate adjustment of the magnetic field axis and the beam direction.

At 1 T, the discrepancy is most likely also caused by dead volume effects that are prominent for this magnetic flux density (Malkov and Rogers 2017, Spindeldreier et al 2017).

We considered magnetic flux densities up to 2.5 T in order to provide input for future development of new generations of MR-linacs, where higher magnetic flux densities strengths may be relevant.

In this context, the results show that lower magnetic flux densities are not equivalent to a lower impact on ionization chambers. This is because the effect of the magnetic field on ionization chamber readings is at its maximum at approximately 1 T and decreases for both lower and higher magnetic flux densities.

In addition to the results presented here, we also simulated the setup used by Smit et al (2013) and were able to corroborate their correction factor of 0.953(10) for an ionization chamber of type NE2571 placed inside a PMMA phantom with our simulation experiment (PMMA, $\alpha = 270^\circ$), resulting in a correction factor of 0.9529(26).
Conclusion

EGSnrc Monte Carlo simulations based on the new, enhanced algorithm for electron transport in EEMF confirm previous results for ionization chamber corrections in external magnetic fields. Correction factors for eight chambers were simulated for current MR-linac systems, and can thus now be used for reference dosimetry and further validation.

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Appendix

Fano cavity test

The implementation of complex ionization chamber geometries in EGSnrc can lead to errors resulting from faulty geometry definitions. A deficient geometry definition may result in inaccurate particle transport across geometry borders; a Fano cavity test is an adequate tool for verification of the implementation of geometries. The Fano cavity test was adapted as it is presented in previous publications (Sempau and Andreo 2006, de Pooter et al 2015, Malkov and Rogers 2016). All material cross sections were changed to those of water. The volumetric mass density inside the sensitive volume was set to a value that was a thousand times less than the volumetric mass density that was used for other parts of the simulation geometry. For Fano test simulations the ionization chambers’ geometries were embedded in a $10 \times 10 \times 10$ cm$^3$ water phantom. Photon transport was disabled and electrons were sampled isotropic, uniform per unit mass throughout the whole simulation geometry with an initial energy of 1.25 MeV. A detailed description for the calculation of a theoretical value for the absorbed dose in the sensitive volume for this scenario can be found in literature (Malkov and Rogers 2016). The mean doses were scored in the sensitive volumes of all ionization chambers and compared to the corresponding theoretical values. All ionization chamber geometries passed this test with a deviation of less than 0.1% from the theoretical value, the results are presented in figure 4.

Figure 4. Results of the Fano cavity tests for all simulated ionization chamber geometries. For each ionization chamber, the mean dose scored in the sensitive volume under Fano conditions was compared to the corresponding theoretical value.
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