Monte Carlo calculation of detector perturbation and quality correction factors in a 1.5 T magnetic resonance guided radiation therapy small photon beams

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Abstract

Objective. With future advances in magnetic resonance imaging-guided radiation therapy, small photon beams are expected to be included regularly in clinical treatments. This study provides physical insights on detector dose-response to multiple megavoltage photon beam sizes coupled to magnetic fields and determines optimal orientations for measurements. Approach. Monte Carlo simulations determine small-cavity detector (solid-state: PTW60012 and PTW60019, ionization chambers: PTW31010, PTW31021, and PTW31022) dose-responses in water to an Elekta Unity 7 MV FFF photon beam. Investigations are performed for field widths between 0.25 and 10 cm in four detector axis orientations with respect to the 1.5 T magnetic field and the photon beam. The magnetic field effect on the overall perturbation factor (\(P_{\text{MC}}\)) accounting for the extracameral components, atomic composition, and density is quantified in each orientation. The density (\(\rho\)) and volume averaging (\(P_{\text{vol}}\)) perturbation factors and quality correction factors (\(k_{Q,0}\)) accounting for the magnetic field are also calculated in each orientation. Main results. Results show that \(P_{\text{vol}}\) remains the most significant perturbation both with and without magnetic fields. In most cases, the magnetic field effect on \(P_{\text{vol}}\) is 1% or less. The magnetic field effect on \(P_{\rho}\) is more significant on ionization chambers than on solid-state detectors. This effect increases up to 1.564 ± 0.001 with decreasing field size for chambers. On the contrary, the magnetic field effect on the extracameral perturbation factor is higher on solid-state detectors than on ionization chambers. For chambers, the magnetic field effect on \(P_{\text{MC}}\) is only significant for field widths < 1 cm, while, for solid-state detectors, this effect exhibits different trends with orientation, indicating that the beam incident angle and geometry play a crucial role. Significance. Solid-state detectors’ dose-response is strongly affected by the magnetic field in all orientations. The magnetic field impact on ionization chamber response increases with decreasing field size. In general, ionization chambers yield \(k_{Q,0}\) closer to unity, especially in orientations where the chamber axis is parallel to the magnetic field.

1. Introduction

In magnetic resonance-guided radiation therapy (MRgRT), real-time imaging of the target volumes and organs at risk allows online adaptive radiation therapy with no additional dose coming from the imaging system. Future advances in MRgRT are expected to include the regular use of small photon beams to deliver complex radiation therapy. Therefore, it is essential to investigate the effect of the magnetic field on small field dosimetry.
In small field dosimetry, the field size can critically compromise lateral charged particle equilibrium (LCPE). The interplay between the lack of LCPE and the detector density can cause significant perturbation effects (Crop et al. 2009, Scott et al. 2012, Fenwick et al. 2013, Bouchard et al. 2015a, 2015b, International Atomic Energy Agency 2017). Additionally, if the detector size is comparable to the field size, the absorbed dose gradient over the detector sensitive volume can cause volume averaging perturbations, which usually underestimates the absorbed dose at the point of measurement. Moreover, due to the small field collimation, a diminished number of scattered photons can reach the detector compared to broad beams, which affects the dose response by changing the mass energy-absorption coefficients and the mass stopping power ratios (Palmans et al. 2018).

Several studies investigated and quantified the perturbation effects on detector dose response in different non-conventional beams such as in intensity-modulated radiation therapy (Bouchard et al. 2009, Kamio and Bouchard 2014, Desai et al. 2019), in small fields (Crop et al. 2009, Scott et al. 2012, Fenwick et al. 2013, Bouchard et al. 2015a, 2015b) and in the presence of magnetic fields (Looe et al. 2017, Spindeldreier et al. 2017). This approach uses Monte Carlo simulations to decompose the detector into separate components. Each component corresponds to a perturbation of the ideal conditions established in cavity theory. These perturbations are due to the detector’s geometry, atomic composition, density, and cavity size. During calculation, each of these components is removed one by one, and the corresponding perturbation factor is calculated at each stage. In small fields, the two dominant perturbation factors are: (1) the volume averaging perturbation factor (Bouchard et al. 2009, Crop et al. 2009, Scott et al. 2012) and (2) the density perturbation factor (Bouchard et al. 2009, Scott et al. 2012, Underwood et al. 2013). Scott et al. demonstrated a significant variation of the ratio of dose-to-water over dose-to-detector-in-water with field size for ion chambers, silicon diodes, and diamond detectors. In general, it was found that this variation was mainly due to the change in density with respect to the surrounding medium; high-density detectors tend to over-respond, and low-density detectors to under-respond (Scott et al. 2012). It was also shown that density and volume averaging perturbation factors are constant for large field sizes and diverge for smaller field sizes, the specific field size at which the change occurs depends on detector size (Scott et al. 2012). The same behaviour was found in Monte Carlo calculations of quality correction factors with respect to field size for ionization chambers and diodes irradiated with 6 MV beams (Francescon et al. 2011).

Analogously to small photon beams, photon beams coupled to magnetic fields involve violation of charged particle equilibrium (CPE) with a much stronger degree than for broad beams for which transient CPE and full lateral CPE are achieved at some reference position. While small fields compromise lateral CPE, the presence of an external magnetic field violates CPE through the interplay between the detector density and the Lorentz force, and more specifically, the relation between the electron gyration radius and its energy. That is, even when neglecting photon attenuation and scatter, CPE cannot be assured in detectors unless the mass density of the detector scales with the magnetic field strength (Bouchard and Bielajew 2015, Bouchard et al. 2015c, De Pooter et al. 2015); this is not the case in MRgRT in general as the detector is not water-equivalent. As Fanos theorem governs ionization chamber dosimetry of photon beams (Fano 1954), one can anticipate the loss of CPE in small photon beams coupled to a magnetic field to introduce further electron fluence perturbations, especially at low-energies since the gyration radius increases with decreasing energy.

The dose response of some commercial ionization chambers in magnetic fields has been characterized in several studies considering different detector axis orientations with respect to the photon beam and the magnetic field (Meijising et al. 2009, Reynolds et al. 2013, Smitt et al. 2013, O’Brien et al. 2016, Spindeldreier et al. 2017). In a previous study focused on the response of small-cavity ionization chambers (Cervantes et al. 2020), it was shown that for small-cavity ionization chambers, the effect of the magnetic field in dose deposition also varies with the geometry or size of the detector as well as with the orientation of the chamber with respect to the magnetic field and the irradiation beam. Moreover, it was confirmed that the effective sensitive volume must be modelled for small-cavity chambers by removing the dead volume adjacent to the guard electrode where there is ineffective charge collection (Spindeldreier et al. 2017, Cervantes et al. 2020).

In addition to the complexity of chamber response modeling in the presence of magnetic fields, currently, there are no available codes of practice or guidelines for the reference dosimetry of MR-Linacs, neither for reference field size nor small fields (Kurz et al. 2020, de Pooter et al. 2021). Thus, one objective of this study is to provide physical insights into the effects of magnetic fields on detector response by calculating perturbation factors for three commercial small-cavity ionization chambers and two solid-state detectors irradiated by beams of multiple sizes. Another objective is to determine experimental conditions under which perturbations are minimized. Finally, this study provides quality correction factor data for these commercial detectors using Elekta Unity phase space files and different field size settings.
2. Materials and methods

2.1. Dosimetry formalism

In reference dosimetry, the quantity of interest is absorbed dose at a point in water. This quantity is determined via measurements using detectors with a finite cavity made of a specific material. The atomic composition and density of the cavity are usually different from that of water. There is also a wide variation in shape and dimension of detector cavities commercially available. The present study follows the approach of Bouchard et al. (2015b) to determine the perturbation and quality correction factors of different detectors. The absorbed dose in water relative to the cavity is defined by a ratio $f(Q)$ depending on the atomic properties of the detection medium, the geometry of the detector, and the beam quality $Q$:

$$f(Q) = \frac{D_w}{D_{det}} = \left(\frac{Z}{A}\right)_{det}^{w_{med}} P(Q),$$

where the $D_w$ is the absorbed dose at the point of measurement in water, $D_{det}$ is the averaged absorbed dose in the detector, $Z$ is the atomic number, $A$ is the atomic mass, $\left(\frac{Z}{A}\right)_{det}^{w_{med}}$ is the ratio of water atomic properties to the detector medium, $P(Q)$ is the total perturbation factor and $Q$ is the beam quality in its general meaning, i.e. it represents the particle phase space distribution surrounding the detector as a consequence of the irradiation conditions (field size, depth, magnetic field strength, etc).

2.2. Decomposition of the perturbation factors

The detector in water perturbs the dose deposition because of the extracameral components, the differences in atomic composition and mass density of the detector materials (i.e. hence in atomic cross sections and density-effect corrections), and the finite size of the detecting cavity. The overall perturbation factor is defined as the product of perturbation subfactors associated with the detector’s specific components, i.e. stem, central electrode, wall cavity, atomic composition, and density of the sensitive material. The decomposition of subfactors is illustrated in figure 1. The perturbation factor and subfactors are determined with Monte Carlo simulations, and they are defined as:

$$P = P_{MC} P_{vol} = P_{ext} P_{med} P_{\rho} P_{vol},$$

where $P_{MC}$ is the overall perturbation factor. It is composed of the extracameral (stem, central electrode and cavity wall) perturbation factor, $P_{ext}$, of the medium perturbation factor, $P_{med}$, and of the density perturbation factor, $P_{\rho}$. $P_{vol}$ is the volume averaging perturbation factor. These subfactors, $P_{i}$, are illustrated in figure 1 and are defined by Bouchard et al’s formalism (Bouchard et al 2015b):

$$P_i = \frac{D_{i+1}}{D_i} \left(\frac{Z}{A}\right)_{i+1},$$

where $D_{i+1}/D_i$ is the dose ratio in the geometry $i + 1$ without the perturbing element relative to that of the geometry $i$ including it and $\left(\frac{Z}{A}\right)_{i}$ is the electron density (in mol$^{-1}$) of the cavity medium of geometry $i$. A calculation chain of perturbation factors is chosen arbitrarily, yet consistently, as follows. The first geometry ($i = 1$) corresponds to the full detector, as shown in figure 1. The second geometry ($i = 2$) corresponds to the bare cavity filled with air. The third geometry ($i = 3$) is a bare cavity filled with an artificial water vapor medium, noted $w^*$, having the same atomic properties as water but with the electron density of air. The fourth geometry

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**Figure 1.** Decomposition of perturbation factors using an arbitrary, yet consistent, route. The perturbation factors on top of the arrows corresponds to the ratio of each adjacent cavity dose.
(i = 4) is the cavity filled with water. The last geometry (i = 5) is a sphere of 1 mm radius meant to represent a water point. The ratio \( \left( \frac{Z}{\lambda} \right)^{i+1} \) is unity except for the case \( i = 2 \).

### 2.3. Quality correction factors

Magnetic field correction factors accounting for the magnetic field have been defined by several authors (O’Brien et al. 2016, Malkov and Rogers 2018, van Asselen et al. 2018, Cervantes et al. 2020) using inconsistent notation, such as \( k_B \) or \( k_{QB} \). This quality correction factor is usually the ratio of calibration coefficients with and without magnetic fields. Using the methodology proposed by Bouchard et al. (2015a, 2015b), the quality correction factor \( k_{Qf(Qf)} \) (following IAEA-AAPM notation (Alfonso et al. 2008)) is calculated as follows:

\[
k_{Qf(Qf)} = \frac{P_{Qf}}{P_{Qf}^f},
\]

where the subscripts \( Q \) and \( Q_B \) indicate the beam quality in the absence and presence of a magnetic field, respectively. The superscripts \( f \) and \( f_B \) represent the field sizes in the absence and presence of a magnetic field, respectively.

### 2.4. Monte Carlo simulations

The Monte Carlo calculations of absorbed dose-to-detector are performed with the EGSnrc user code egs_chamber (Kawrakow et al. 2017). The five detectors studied are three small-cavity ionization chambers models: PTW31010, PTW31021, and PTW31022 (PTW, Freiburg, Germany), the unshielded silicon diode PTW60012, and the microDiamond detector PTW60019. The ionization chamber models have been previously validated with an experimental setup and Monte Carlo simulations (Cervantes et al. 2020). The chamber active sensitive volumes were defined with COMSOL Multiphysics 5.5 (COMSOL Inc., Burlington, MA, USA) calculations of the electric field accounting for the absence of ion collection near the guard electrode. The silicon diode model is based on a previously published model built from the manufacturer blueprints (Kamio and Bouchard 2014), and the microDiamond detector model is also built from blueprints but has not been used in previous work. The detector is placed inside a water tank phantom of 30 × 30 × 30 cm\(^2\) at 10 cm depth. The source-to-surface distance (SSD) is set to 133.5 cm, and the field widths are 10, 5, 3, 2, 1, 0.75, 0.5 and 0.25 cm at the isocenter. For field widths between 1 cm and 10 cm, 7 MV FFF photon beam phase spaces of the Elekta Unity MR-Linac, kindly provided by the manufacturer (Elekta Instrument AB Stockholm, Sweden), are used. These phase spaces consider the transport throughout the MR-linac components, as shown in reference (Roberts et al. 2021), and they are scored at 129.5 cm from the source.

The smallest feasible field in the Elekta Unity MR-Linac is 1 × 1 cm\(^2\). Smaller field sizes are also investigated, although they are not clinically relevant at the moment. They are academically interesting since they provide insights into the interplay between magnetic fields and small fields. To produce these smaller phase spaces, the egs_collimated_source library is used to generate a collimated square field at the isocenter using the spectral distribution extracted from the 1 × 1 cm\(^2\) phase space.

Since the beam is perpendicular to the magnetic field, in principle, there can exist six orientations where the chamber axis forms either an orthogonal system with the other two axes or is parallel to one axis. However, because of the symmetry of cylindrical detectors and that the beam should never hit first the detector stem and cables, by symmetry of two out of six orientations, only four chamber axis orientations are considered and are illustrated in figure 2: (1) chamber axis perpendicular to the magnetic field and parallel to the beam; (2) chamber axis perpendicular to the magnetic field and perpendicular to the beam with the Lorentz force pointing towards the stem, (3) chamber axis perpendicular to the magnetic field and perpendicular to the beam with the Lorentz force pointing towards the tip and (4) chamber axis perpendicular to the beam and parallel to the magnetic field. The magnetic field is implemented with the enhanced electromagnetic field macro (Malkov and Rogers 2016). Calculation times are optimized by implementing variance reduction techniques such as cross-section enhancement, range-rejection-based Russian Roulette, and intermediate phase-space storing (Wulff et al. 2008). The egs_chamber default parameters are used except for EM ESTEPE = 0.01, the threshold energy for electrons \( AE = 0.512 \text{ MeV} \) and for photons \( AP = 0.001 \text{ MeV} \).

### 2.5. Uncertainty analysis

As explained in our previous study (Cervantes et al. 2020), for the quality correction factors, the sources of uncertainty associated with Monte Carlo simulations of the five detectors dose response are: (1) the type A statistical uncertainty, \( \sigma_{\text{stat}} \), (2) a type B due to the inconsistencies of the transport algorithm, set to be \( \sigma_{\text{Fano}} = 0.13\% \), coming from the Fano test of the ionization chambers, (3) a type B emerging from the uncertainty of the physical data used in the Monte Carlo code, \( \sigma_{\text{data}} = 0.2\% \) (Muir and Rogers 2010,
Wulff et al (2010), applicable to all of the detector simulations, and (4) the type B detector geometry uncertainty accounting for the discrepancies between blueprints and the real chamber geometry and for the uncertainty in the characterization of the dead volume, the values of $\sigma_{\text{geom}}$ are set to 0.1% for the silicon and microDiamond detectors (these detectors do not have a dead volume) and to 0.26%, 0.24% and 0.17% for PTW31010, PTW31021 and PTW31022, respectively, more details on the determination of these values can be found in reference (Cervantes et al 2020). Then the combined uncertainty of the quality correction factors is obtained by adding these values in quadrature. For the perturbation factor calculations, which are meant only to provide physical insights, only the type A statistical uncertainty is considered.

3. Results

The perturbation factors of five radiation detectors are evaluated with Monte Carlo simulations: three ionization chambers and two solid-state detectors. Calculations include eight squared field sizes, $f$, between $0.25 \times 0.25$ and $10 \times 10$ cm$^2$ at 0 and 1.5 T. Four detector orientations in an Elekta’s Unity MR-Linac setup are studied. In section 3.1, results of the perturbation factors in the absence of magnetic fields are presented, and in section 3.2 the effect of the magnetic field on each perturbation factor is presented.

3.1. Perturbation factors in the absence of magnetic fields

3.1.1. Density perturbation factor, $P_\rho$

The density perturbation factor at 0 T is presented on the left side of figures 3 and 4 for solid-state detectors and ionization chamber, respectively. For the solid-state detectors, $P_\rho$ is independent of field size and orientation, and it is close to unity by less than 1.5%. For ionization chambers, for $f > 1 \times 1$ cm$^2$, $P_\rho$ is mostly constant and close to 1. However, for $f \leq 1 \times 1$ cm$^2$, $P_\rho$ increases with decreasing field size. Over all chamber orientations, the maximal perturbation ($2.003 \pm 0.001$) occurs for the PTW31010 chamber.

3.1.2. Overall perturbation factor, $P_{MC}$

The overall perturbation factor at 0 T for the five detectors is shown on the left side of figures 5 and 6 for each orientation. For the solid-state detectors, $P_{MC}$ behaves similarly in the four orientations; $P_{MC}$ remains mostly constant for $f > 1 \times 1$ cm$^2$ and decreases for the smaller fields. For the ionization chambers, in all orientations, $P_{MC}$ is close to unity for $f > 1 \times 1$ cm$^2$. For $f \leq 1 \times 1$ cm$^2$, $P_{MC}$ increases with decreasing field size. Note that the variation rate is different for each chamber model. The semiflex 3D (PTW31021) presents the maximal perturbation: $P_{MC} = 1.782 \pm 0.001$. It is noteworthy that at the 0.5 cm field width, the PTW31010 chamber falls out of the general trend. CPE is lost because the sensitive volume is larger than the field size. Indeed, this behaviour was confirmed with an alternate method by estimating the dose response behaviour with respect to field size using Monte Carlo dose response functions (defined in Kamio and Bouchard (2014)).
3.1.3. Volume averaging perturbation factor

The volume averaging perturbation factor at 0 T is presented as a function of the field size in each orientation, left side of Figures 7 and 8. For solid-state detectors, the volume averaging perturbation is negligible for \( f > 0.25 \times 0.25 \text{ cm}^2 \); \( P_{\text{vol}} \) is mostly constant and very close to unity. For the smallest field size, \( P_{\text{vol}} \) increases 1.5\% from unity.

For ionization chambers, for \( f > 1 \times 1 \text{ cm}^2 \), \( P_{\text{vol}} \) is independent of field size and very close to 1. For the smaller field sizes, \( P_{\text{vol}} \) increases as the field size decreases. The smallest chamber (PTW31022) presents the

Figure 3. On the left side, \( P_{\rho} \) of solid-state detectors for four orientations as function of the field sizes at 0 T. On the right side, the effect of the magnetic on \( P_{\rho} \) as a function of the field size.

Figure 4. On the left side, \( P_{\rho} \) of ionization chambers for four orientations as function of the field sizes at 0 T. On the right side, the effect of the magnetic on \( P_{\rho} \) as a function of the field size.
smallest $P_{\text{vol}}$, attaining a maximal value of $1.150 \pm 0.001$, in orientation 2. For the PTW31010 and PTW31021 chambers, $P_{\text{vol}}$ rises rapidly in the smallest field sizes, reaching the maximal values of $2.486 \pm 0.001$ (orientation 1) and $1.831 \pm 0.001$ (orientations 2 and 3), respectively.

3.2. Effect of the magnetic field on the perturbation factors

3.2.1. Density perturbation factor, $P_\rho$

The magnetic field effect is quantified by the ratio of $P_\rho(1.5 \, \text{T})$ to $P_\rho(0 \, \text{T})$ in each orientation, on the right side of figures 3 and 4. For the solid-state detectors, the magnetic field effect on $P_\rho$ is 1% or less from unity, over all field sizes.
sizes and orientations. For the ionization chambers, for \( f > 1 \times 1 \text{ cm}^2 \), the effect of the magnetic field is mostly constant and around 1%, the exact value depends on detector model and orientation. For \( f \leq 1 \times 1 \text{ cm}^2 \), this effect increases abruptly, and it can reach as high as 1.564 ± 0.001 (PTW31010, orientation 1). Over all field sizes and orientations, the smallest density perturbation caused by the magnetic field is observed for the smallest chamber (PTW31022). In general, the magnetic field impact on \( P_{\rho} \) is lower in orientations 2 and 4. In orientation 4, the magnetic field’s effect is smaller because it is parallel to the chamber axis. In orientation 2, electrons are
deflected towards the stem and towards the dead volume, where the collection is inefficient. This results in a decrease of signal in magnetic fields, which could be why the magnetic field effect is smaller in $P_\rho$.

3.2.2. Overall perturbation factor, $P_{MC}$

The magnetic field effect on $P_{MC}$, in each orientation, is presented on the right side of figures 5 and 6. For ionization chambers, in all orientations, for $f \geq 1 \times 1 \text{ cm}^2$, the magnetic field effect is 3% or less from unity. As field size decreases, this effect increases to a maximal value that depends on the orientation. The largest impact considering all field sizes and orientations is $1.257 \pm 0.001$, occurring for the chamber PTW31021 in orientation 3.

For the solid-state detectors, $P_{MC}$ behaves similarly in all orientations in the absence of a magnetic field. However, when the magnetic field is present, $P_{MC}$ varies with orientation, shown in figure 5. Since the magnetic field effect on $P_\rho$ is minor, then the increase on $P_{MC}$ in magnetic fields mainly comes from the extracameral components perturbations. This is why there are large variations in the magnetic field effect among the orientations; in each one, the beam encounters different geometrical components.

3.2.3. Volume averaging perturbation factor

The magnetic field effect on $P_{vol}$ in each orientation is presented on the right side of figures 7 and 8. For solid-state detectors, the magnetic field effect on $P_{vol}$ is 1% or less from unity. For ionization chambers, the magnetic field affects $P_{vol}$ in different ways depending on chamber orientation. In orientations 1 and 4, the magnetic field effect is mostly independent of field size, and the variations are around 1% or less from unity. In contrast, the magnetic field has a noticeable impact on chambers PTW31021 and PTW31022; these over-respond and under-respond, in orientations 2 and 3, respectively, for the smaller fields.

3.3. Quality correction factors

The quality corrections factors for detectors: PTW60012, PTW60019, PTW31010, PTW31021 and PTW31022 are presented in tables 1–5, respectively. Over all the detectors, chamber PTW31022 has the $k_{Q\phi Q}^{f=0}$ closer to unity. In particular, in orientations 1 and 4, for $f > 0.25 \times 0.25 \text{ cm}^2$, $k_{Q\phi Q}^{f=0}$ corrections are smaller than 1.5%.

Orientations 2 and 3 present larger $k_{Q\phi Q}^{f=0}$ over all field sizes.

4. Discussion

4.1. Perturbation factors in the absence of magnetic fields

4.1.1. Density perturbation factor, $P_\rho$

Scott et al (2012) investigated the effect of density and atomic composition on the dose response of several detectors, including an unshielded silicon detector, a diamond detector, and a 3D pinpoint chamber PTW31016 (previous model to PTW31022) in small photon fields, in the absence of a magnetic field. For the silicon diode, Scott et al reported a $P_\rho$ value around 0.95, while our results for the PTW60012 diode model are found between 0.986 ± 0.002 and 0.993 ± 0.002 depending on the orientation. For the microDiamond detector, in both studies, the values decrease below unity. However, here $P_\rho$ remains very close to unity (0.995 ± 0.001 to 0.999 ± 0.001) in all orientations, whereas in their study, it decreases to approximately 0.85. The differences may be attributed to variations in the model geometry; their detectors are simply modelled by a pixel of 2.26 mm of diameter and thickness of 0.26 mm for the diamond and thickness of 0.06 mm for the silicon diode, while in the present study, the solid-state detectors are much smaller, as they are based on the manufacturer blueprints.

Table 1. Calculated quality correction factors for the PTW60012 in a 1.5 T magnetic field, in four orientations, for multiple square field sizes. Uncertainties are estimated using the method described in section 2.5.

| Field size (cm²) | Orientation 1 | Orientation 2 | Orientation 3 | Orientation 4 |
|-----------------|--------------|--------------|--------------|--------------|
| 10 × 10         | 1.097 ± 0.006| 0.990 ± 0.009| 0.880 ± 0.010| 1.005 ± 0.009|
| 5 × 5           | 1.101 ± 0.007| 0.980 ± 0.009| 0.877 ± 0.009| 1.004 ± 0.009|
| 3 × 3           | 1.107 ± 0.006| 0.984 ± 0.011| 0.875 ± 0.009| 1.002 ± 0.011|
| 2 × 2           | 1.097 ± 0.006| 0.984 ± 0.008| 0.868 ± 0.008| 0.994 ± 0.009|
| 1 × 1           | 1.076 ± 0.004| 1.002 ± 0.008| 0.857 ± 0.007| 0.984 ± 0.008|
| 0.75 × 0.75     | 1.056 ± 0.003| 1.011 ± 0.005| 0.853 ± 0.003| 0.976 ± 0.005|
| 0.5 × 0.5       | 1.029 ± 0.003| 0.994 ± 0.005| 0.855 ± 0.003| 0.959 ± 0.005|
| 0.25 × 0.25     | 1.006 ± 0.003| 0.984 ± 0.005| 0.875 ± 0.004| 0.954 ± 0.005|
In their study, in the three chambers studied here. It is constant for Phys. Med. Biol.

For ionization chambers, the behaviour of $P_\rho$ was approximately 1.5 at 0.25 cm × 0.75 cm, and it increases as the field size decreases. In their study, $P_\rho$ was approximately 1.5 at 0.25 cm × 0.25 cm for the 3D pinpoint chamber. This is close to our

### Table 2. Calculated quality correction factors for the PTW60019 in a 1.5 T magnetic field, in four orientations, for multiple square field sizes. Uncertainties are estimated using the method described in section 2.5.

| Field size (cm²) | Orientation 1 | Orientation 2 | Orientation 3 | Orientation 4 |
|------------------|---------------|---------------|---------------|---------------|
| 10 × 10          | 1.175 ± 0.009 | 1.208 ± 0.010 | 0.845 ± 0.008 | 0.999 ± 0.007 |
| 5 × 5            | 1.181 ± 0.005 | 1.227 ± 0.007 | 0.847 ± 0.007 | 0.993 ± 0.008 |
| 3 × 3            | 1.181 ± 0.005 | 1.231 ± 0.008 | 0.845 ± 0.008 | 0.994 ± 0.008 |
| 2 × 2            | 1.165 ± 0.004 | 1.215 ± 0.007 | 0.836 ± 0.006 | 0.989 ± 0.007 |
| 1 × 1            | 1.090 ± 0.002 | 1.138 ± 0.006 | 0.828 ± 0.005 | 0.962 ± 0.005 |
| 0.75 × 0.75      | 1.050 ± 0.003 | 1.099 ± 0.003 | 0.825 ± 0.003 | 0.950 ± 0.003 |
| 0.5 × 0.5        | 1.025 ± 0.002 | 1.043 ± 0.003 | 0.835 ± 0.003 | 0.939 ± 0.003 |
| 0.25 × 0.25      | 1.004 ± 0.003 | 1.013 ± 0.003 | 0.860 ± 0.003 | 0.941 ± 0.003 |

### Table 3. Calculated quality correction factors for the PTW31019 in a 1.5 T magnetic field, in four orientations, for multiple square field sizes. Uncertainties are estimated using the method described in section 2.5.

| Field size (cm²) | Orientation 1 | Orientation 2 | Orientation 3 | Orientation 4 |
|------------------|---------------|---------------|---------------|---------------|
| 10 × 10          | 0.987 ± 0.004 | 1.007 ± 0.004 | 0.985 ± 0.004 | 0.995 ± 0.004 |
| 5 × 5            | 0.988 ± 0.004 | 1.008 ± 0.004 | 0.983 ± 0.004 | 0.990 ± 0.004 |
| 3 × 3            | 0.993 ± 0.005 | 1.012 ± 0.005 | 0.992 ± 0.005 | 0.993 ± 0.005 |
| 2 × 2            | 0.994 ± 0.005 | 1.011 ± 0.005 | 0.995 ± 0.005 | 0.998 ± 0.005 |
| 1 × 1            | 1.010 ± 0.005 | 1.000 ± 0.005 | 1.006 ± 0.005 | 1.017 ± 0.005 |
| 0.75 × 0.75      | 1.023 ± 0.004 | 0.990 ± 0.004 | 1.017 ± 0.004 | 1.040 ± 0.004 |
| 0.5 × 0.5        | 1.152 ± 0.004 | 1.060 ± 0.004 | 1.087 ± 0.004 | 1.169 ± 0.004 |
| 0.25 × 0.25      | 1.136 ± 0.004 | 1.088 ± 0.004 | 1.116 ± 0.004 | 1.179 ± 0.004 |

### Table 4. Calculated quality correction factors for the PTW31021 in a 1.5 T magnetic field, in four orientations, for multiple square field sizes. Uncertainties are estimated using the method described in section 2.5.

| Field size (cm²) | Orientation 1 | Orientation 2 | Orientation 3 | Orientation 4 |
|------------------|---------------|---------------|---------------|---------------|
| 10 × 10          | 0.974 ± 0.005 | 1.017 ± 0.004 | 0.972 ± 0.004 | 1.016 ± 0.004 |
| 5 × 5            | 0.975 ± 0.004 | 1.022 ± 0.004 | 0.976 ± 0.004 | 1.015 ± 0.004 |
| 3 × 3            | 0.975 ± 0.004 | 1.025 ± 0.004 | 0.976 ± 0.004 | 1.015 ± 0.005 |
| 2 × 2            | 0.978 ± 0.005 | 1.022 ± 0.005 | 0.988 ± 0.004 | 1.018 ± 0.005 |
| 1 × 1            | 0.986 ± 0.010 | 0.995 ± 0.005 | 1.020 ± 0.005 | 1.023 ± 0.005 |
| 0.75 × 0.75      | 0.980 ± 0.004 | 0.973 ± 0.005 | 1.046 ± 0.004 | 1.037 ± 0.004 |
| 0.5 × 0.5        | 1.026 ± 0.004 | 0.967 ± 0.004 | 1.130 ± 0.006 | 1.095 ± 0.004 |
| 0.25 × 0.25      | 1.201 ± 0.004 | 1.066 ± 0.004 | 1.350 ± 0.004 | 1.227 ± 0.004 |

### Table 5. Calculated quality correction factors for the PTW31022 in a 1.5 T magnetic field, in four orientations, for multiple square field sizes. Uncertainties are estimated using the method described in section 2.5.

| Field size (cm²) | Orientation 1 | Orientation 2 | Orientation 3 | Orientation 4 |
|------------------|---------------|---------------|---------------|---------------|
| 10 × 10          | 0.998 ± 0.004 | 1.027 ± 0.005 | 0.994 ± 0.004 | 0.997 ± 0.004 |
| 5 × 5            | 0.999 ± 0.005 | 1.025 ± 0.005 | 0.992 ± 0.005 | 0.990 ± 0.005 |
| 3 × 3            | 1.001 ± 0.004 | 1.029 ± 0.005 | 0.985 ± 0.005 | 0.996 ± 0.005 |
| 2 × 2            | 1.005 ± 0.004 | 1.026 ± 0.004 | 0.997 ± 0.004 | 0.998 ± 0.004 |
| 1 × 1            | 0.998 ± 0.004 | 1.012 ± 0.008 | 1.012 ± 0.004 | 0.998 ± 0.004 |
| 0.75 × 0.75      | 0.998 ± 0.004 | 0.990 ± 0.004 | 1.023 ± 0.004 | 1.002 ± 0.004 |
| 0.5 × 0.5        | 1.003 ± 0.004 | 0.972 ± 0.004 | 1.048 ± 0.004 | 1.011 ± 0.004 |
| 0.25 × 0.25      | 1.080 ± 0.003 | 0.991 ± 0.003 | 1.187 ± 0.003 | 1.091 ± 0.003 |
results for the same field size where $P_f$ of PTW31022 varies between 1.439 ± 0.001 and 1.461 ± 0.001 depending on the orientations, see the left side of figure 3.

4.1.2. Overall perturbation factor, $P_{MC}$

The overall perturbation factor is the product of the perturbations coming from extracameral components and the variations in the detector’s atomic properties and density with respect to the medium. Volume average effects aside, the perturbations of dose response in small fields are dominated by the effect of density and the presence of extracameral components, rather than by the atomic composition (Crop et al 2009, Scott et al 2012, Bouchard et al 2015a, 2015b). Crop et al (2009) reported perturbations of up to 1% from unity coming from the central electrode and the wall cavity for two pinpoint ionization chambers in small fields. Bouchard et al (2015b) showed that the extracameral perturbations could be significant and comparable to density perturbation factors in small photon beams for detectors with higher mass density than water, which is the case for the solid-state detectors.

4.1.3. Volume averaging perturbation factor

For solid-state detectors, Scott et al also performed simulations of $P_{vol}$ for two pixel sizes (1.33 and 2.26 mm of diameter and 0.26 mm thick), representing the volume of small field detectors (Scott et al 2012). Their results showed a similar behaviour of $P_{vol}$ at large fields. However, for the smallest field, the increase of $P_{vol}$ is significant, approximately 10%, which is larger than the variation observed in this study. This is expected as the sensitive volumes are submillimetric: 0.25 mm$^3$ and 0.004 mm$^3$ for the PTW60012 and PTW60019, respectively. On the other hand, the ionization chamber results of this work are consistent with the findings of (Scott et al 2012) for all fields.

4.2. Effect of the magnetic field on the perturbation factors

4.2.1. Density perturbation factor, $P_d$

For each detector, $P_d$ behaves similarly in the four orientations with and without magnetic fields, as seen in figures 3 and 4. The behaviour of $P_d$ is related to the charged particle fluence in the cavity and, thus, to the cavity size. For ionization chambers, the cavity density is three orders of magnitude smaller than water density. In such low-density materials, the production of secondary electrons diminishes; hence the electron fluence inside the cavity is smaller than in a cavity filled with the surrounding medium. Additionally, as field size decreases, there is a further reduction of the electron fluence in the cavity, explaining the rise on $P_d$. In contrast, for the solid-state detectors, the cavity and medium densities are of the same order of magnitude (silicon 2.33 g cm$^{-3}$ and diamond 3.53 g cm$^{-3}$); thus, the density perturbation is small and quasi-independent of field size in the absence and presence of a magnetic field.

In the presence of a magnetic field, when the beam enters the artificial water vapor cavity (i.e. water atomic composition with air electron density), the electron mean free path increases, and electrons become more susceptible to the Lorentz force. In particular, the low-energy electrons would be more likely to get trapped in air cavities and deposit their energy locally. In contrast, the high-energy electrons would be more likely to escape from the cavity. However, since the main contribution to dose comes from low-energy electrons, a dose increase would be expected in the presence of a magnetic field.

4.2.2. Overall perturbation factor, $P_{MC}$

For the ionization chambers, $P_d$ is the dominant factor within $P_{MC}$. Therefore, $P_{MC}$ follows the general trend of $P_d$ in all orientations. However, there are small variations in the magnetic field effect among the orientations. These differences might come from variations in the geometry depending on the incidence of the beam. For instance, in orientation 1, the central electrode is aligned with the photon beam, and since it has a mass density remarkably higher than air (i.e. approximately 2.34 g cm$^{-3}$), the central electrode produces more electrons which increases the electron fluence in the cavity. Orientations 2 and 3 are similar but with opposite magnetic field directions. In orientation 3, there is a slight under-response of the chambers compared to orientation 2. This could be explained because electrons are, on average, either deflected towards or away from the stem, for orientations 2 and 3, respectively. In orientation 4, the magnetic field is parallel to the chamber, and the geometry plays a less critical role because of the symmetry in the experimental setup and in the chamber.

For solid-state detectors, in orientation 1, the magnetic field effect on $P_{MC}$ increases with field size until a plateau is reached for $f > 1 \times 1$ cm$^2$. At larger fields, scattering increases the fluence of low-energy electrons towards the solid-state detectors. However, it seems that these low-energy electrons are not reaching the sensitive volume since $P_{MC}(1.5 \ T)$ is actually increasing. Even if low-energy electrons are more susceptible to the magnetic field, the electron path also depends on the medium density; thus, components with high density surrounding the active volume could be responsible for the decrease in electron fluence. To support these
physical insights, figure 9 illustrates the interplay between medium density and the magnetic field with two dose maps of a cavity with different density in a $10 \times 10 \times 10$ cm$^3$ water phantom irradiated with a $2 \times 2$ cm$^2$ field at 1.5 T. In figure 9(a), where the cavity material is air, there is an extra dose deposition at the water-air upstream interface because of the electron return effect (ERE), as explained by Raaijmakers et al (2005), and the dose deposition decreases at the air-water downstream interface (on the air side). In figure 9(b), the opposite effect is observed if the cavity has a higher density than water, diamond in this case, and dose deposition diminishes at the water-diamond upstream interface and increases at the diamond-water downstream interface.

Inside the solid-state detector, the materials have a higher density than water. In fact, for the microDiamond, there are materials with a density as high as 8.44 g cm$^{-3}$, and just beside the sensitive volume, there is a large (compared to the sensitive volume) layer of diamond with a density of 3.53 g cm$^{-3}$. The high-density materials surrounding the sensitive volume are likely to be absorbing the majority of the scattered electrons, which would reduce the electron fluence in the cavity and increase the perturbations of $P_{MC}$. Also, it has been experimentally observed that, for large fields, the angular sensitivity of the microDiamond detector is intensified in the presence of magnetic fields, and this detector is not suitable for profile characterization nor for determination of large-field beam parameters (Woodings et al 2018).

For orientations 2 and 3, the silicon diode exhibits a relatively small dependence on the field size, while this is not the case for the microDiamond detector, suggesting the role of the extracameral components on electron fluence variations. In orientation 2, the magnetic field is perpendicular to the chamber axis, and the Lorentz force main direction is towards the stem. The stem of the microDiamond is more heterogeneous and with more high-density materials, while the stem of the silicon diode is mostly air. This could explain the different behaviour between the solid-state detectors in orientation 2. In orientation 3, electrons are, on average, deflected towards the tip where the geometry is more homogeneous, which justifies a similar behaviour of the magnetic field effect on both solid-state detectors. In orientation 4, the magnetic field effect remains relatively constant with field size.

4.2.3. Volume averaging perturbation factor
The notable effect of the magnetic field in the over-response and under-response in chambers PTW31021 and PTW31022, in orientations 2 and 3, respectively at the smaller fields could be attributed to the spherical symmetry of the chambers. The point of measurement is equidistant to the tip and to the stem. Also, the dead volumes adjacent to the guard electrodes correspond to 23.00% (PTW31021) and 18.45% (PTW31022) of their sensitive volume (Cervantes et al 2020). The presence and size of the dead volumes could explain the different behaviour between the solid-state detectors in orientation 2. In orientation 3, electrons are, on average, deflected towards the tip where the geometry is more homogeneous, which justifies a similar behaviour of the magnetic field effect on both solid-state detectors. In orientation 4, the magnetic field effect remains relatively constant with field size.

4.2.4. Quality correction factors
In a review by de Pooter et al (2021), the authors recompiled the published quality correction factors, $k_{Q/Q}$, for two regular-size chambers: PTW30013 and IBA FC65-G from several studies. They applied a criterion to select...
the chamber types and $k_{Q\omega Q}^{vol}$ values to be suitable for comparison. For IBA FC65-G, considering a 1.5 T magnetic field, for a $10 \times 10 \times 10$ cm$^3$ field, the mean values of $k_{Q\omega Q}^{vol}$ are $0.9540 \pm 0.0029$ and $0.9977 \pm 0.0048$, in the perpendicular orientation (orientation 3 in this study) and in the parallel orientations (orientation 4 here), respectively (Wolthaus et al 2016, Billas and Duane 2018, Malkov and Rogers 2018, van Asselen et al 2018, de Prez et al 2019). For the PTW30013, the mean $k_{Q\omega Q}^{vol}$ values are $0.9594 \pm 0.0025$ (orientation 2), $0.9620 \pm 0.0047$ (orientation 3) and $0.9928 \pm 0.0046$ (orientation 4) (Spindeldreier et al 2017, Billas and Duane 2018, Malkov and Rogers 2018, van Asselen et al 2018, de Prez et al 2019, Pojtinger et al 2019, Shipley et al 2019). Comparing the magnitude of quality correction factors between the regular-size chamber (reviewed by de Pooter et al (2021)) and the small-cavity chambers (present study), in a reference field between, in the parallel orientation (orientation 4), the variation of $k_{Q\omega Q}^{vol}$ from unity is below 1.6% for both groups of chambers. However, in the perpendicular orientations (orientations 2 and 3), $k_{Q\omega Q}^{vol}$ values tend to be closer to unity for the small-cavity chambers.

Tekin et al (2020) calculated $k_{Q\omega Q}^{vol}$ factors for the microDiamond PTW 60 019 detector, they found a value around 1.1 for a $4.6 \times 4.6$ cm$^2$, at 1.4 T while the value in this work is 1.181 $\pm$ 0.005 in the same configuration (orientation 1 of this study). The differences can be attributed to the differences in the experimental setup: the measurements in Tekin et al are performed at 5 cm depth, in a water phantom with dimensions $7 \times 20 \times 20$ cm$^3$, using a 6 MV photon beam at a SSD of 110 cm, in this work the calculations are performed at 10 cm depth, in a water phantom with dimensions $30 \times 30 \times 30$ cm$^3$, using a 7 MV FFF photon beam at a SSD of 133.5 cm. Further work should include experimental measurements to validate Monte Carlo calculations of quality correction factors under clinical conditions, for instance using a traceability route with alanine detectors as shown by Billas et al (2021).

5. Suitability for clinical environment

Detector dose response to small photon beams in the presence of magnetic fields is complex. Several perturbation factors are present and compete with each other. In some cases, the perturbations act in opposite directions, so they mitigate each other, while in other cases, they increase the global perturbation factor. This is reflected in the quality correction factors, presented in tables 1–5. According to our results, the two solid-state detectors exhibit large extracranial perturbations in magnetic fields. Thus, these detectors might not be suitable for dosimetry in magnetic fields. Both detectors, especially the microDiamond, present large perturbation factors at larger fields in the recommended measurement setup (orientation 1). Moreover, an experimental study demonstrated that the microDiamond presents a strongly asymmetric response to large radiation fields (Woodings et al 2018).

Since the integration of MR-Linac, several studies have investigated the characteristics and response of ionization chambers for dosimetry measurements in the presence of magnetic fields. The recommended orientation for cylindrical chambers is parallel to the magnetic field (orientation 4 in the present work) (de Pooter et al 2021); this is consistent with our findings since $k_{Q\omega Q}^{vol}$ are closer to unity in orientations 1 and 4 for the ionization chambers. However, the clinical setup of orientation 1 might be more challenging and not feasible in all MR-Linac environments. Since few chamber MC models have been adequately characterized (i.e. dead volume must be removed from the sensitive volume) and validated with experimental measurements, there is limited reliable data of $k_{Q\omega Q}^{vol}$ values. In most cases, these values only exist for a reference field size, as discussed in the previous section. In this investigation, the $k_{Q\omega Q}^{vol}$ values of three small cylindrical chambers are determined in multiple field sizes. The three ionization chambers present similar $k_{Q\omega Q}^{vol}$ values which tend to be closer to unity in orientation 4. When the smaller beam field sizes are used, the recommendation is to use the chamber with the smallest sensitive volume.

6. Conclusion

The magnetic field effect on small-cavity detector dose response to multiple irradiation field sizes is quantified by isolating different perturbation factors in different orientations. Solid-state detectors’ dose response is strongly affected by the magnetic field in all orientations. The extracranial perturbations are amplified in magnetic fields, especially for large fields, while the effect on the density and volume averaging perturbations is lower (1% or less from unity). On the other hand, for ionization chambers, the magnetic field effect is more significant on the density perturbation factor. Volume averaging is the largest perturbation with and without magnetic fields. Orientations where the chamber axis is aligned with the magnetic field yield $k_{Q\omega Q}^{vol}$ factors closer to unity. The
orientation where electrons deflect towards the stem should be avoided. This study also shows that \( k_{f_{Q_{2},Q_{1}}} \) factors close to unity can be obtained for commercial small-cavity chambers in small MRgRT beams.

Quality correction factors are often calculated with Monte Carlo methods. This study reveals the source of dose response perturbations for different detectors in magnetic fields and emphasizes the importance of detailed characterization of the detector geometry in Monte Carlo models accounting for them. Further investigations should focus on particle fluence simulations to provide insights into the interplay between cavity geometry, density, and magnetic field.

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