Experimental determination of magnetic field correction factors for ionization chambers in parallel and perpendicular orientations

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Abstract
Magnetic field correction factors are needed for absolute dosimetry in magnetic resonance (MR)-linacs. Currently experimental data for magnetic field correction factors, especially for small volume ionization chambers, are largely lacking. The purpose of this work is to establish, independent methods for the experimental determination of magnetic field correction factors $k_{B,Q}$ in an orientation in which the ionization chamber is parallel to the magnetic field. The aim is to confirm previous experiments on the determination of Farmer type ionization chamber correction factors and to gather information about the usability of small-volume ionization chambers for absolute dosimetry in MR-linacs. The first approach to determine $k_{B,Q}$ is based on a cross-calibration of measurements using a conventional linac with an electromagnet and an MR-linac. The absolute influence of the magnetic field in perpendicular orientation is quantified with the help of the conventional linac and the electromagnet. The correction factors for the parallel orientation are then derived by combining these measurements with relative measurements in the MR-linac. The second technique utilizes alanine electron paramagnetic resonance dosimetry. The alanine system as well as several ionization chambers were directly calibrated with the German primary standard for absorbed dose to water. Magnetic field correction factors for the ionization chambers were determined by a cross-calibration with the alanine in an MR-linac. Important quantities like $k_{B,Q}$ for Farmer type ionization chambers in parallel orientation and the change of the dose to water due the magnetic field ($c_B$) have been confirmed. In addition, magnetic field correction factors have been determined for small volume ionization chambers in parallel orientation. The electromagnet-based measurements of $k_{B,Q}$ for 7MV/1.5T MR-linacs and parallel ionization chamber orientations resulted in $0.9926(22)$, $0.9935(31)$ and $0.9841(27)$ for the PTW 30013, the PTW 31010 and the PTW 31021, respectively. The measurements based on the second technique resulted in values for $k_{B,Q}$ of $0.9901(72)$, $0.9955(72)$, and $0.9885(71)$. Both methods show excellent accuracy and reproducibility and are therefore suitable for the determination of magnetic field correction factors. Small-volume ionization chambers showed a variation in the resulting values for $k_{B,Q}$ and should be cross-calibrated instead of using tabulated values for correction factors.

1. Introduction
MR-linacs, which combine magnetic resonance (MR) imaging with medical linear accelerators (linacs) are increasingly available for patient treatment in hospitals. From the start of this technical development, a major challenge has been the establishment of a reliable experimental method for the measurement of the absorbed dose to water in an MR-linac environment. This is because the response of ionization chambers, which are routinely used to calibrate the linac output, is known to be influenced by magnetic fields (Meijsing...
et al 2009). Therefore, magnetic field correction factors have been determined in experiments as well as in Monte Carlo simulations for many ionization chambers (Meijising et al 2009, Smit et al 2013, O’Brien et al 2016, Spindeldreier et al 2017, Pojtinger et al 2018, 2019, Malkov and Rogers 2018, van Asselen et al 2018, de Prez et al 2019).

For all MR-linacs, which are commercially available today, the direction of the photon beam is always perpendicular to the magnetic field vector of the $B_0$ field. As thimble type ionization chambers should be positioned so that the ionization chamber axis is perpendicular to the direction of the photon beam, there are two practically relevant orientations for the positioning of an ionization chamber. One orientation is the orientation in which the ionization chamber axis is perpendicular to the magnetic field, and the other orientation is the one in which the ionization chamber axis is parallel to the magnetic field (figure 1). For the perpendicular orientation, the magnetic field corrections also depend on the orientation of the ionization chamber’s tip (Pojtinger et al 2019).

In clinical practice, it is commonly assumed that the parallel orientation is preferable, as it has been shown that the influence of the magnetic field on the response of Farmer-type ionization chambers is smaller compared to the perpendicular orientation (van Asselen et al 2018, de Prez et al 2019). Currently, reliable, experimentally determined correction factors for parallel orientations are only available for Farmer-type ionization chambers. Anyway, it must be mentioned, that some authors have presented results for other types of ionization chambers at international conferences (e.g. Gohil et al 2018). The corrections that can be found in the literature were determined by two different methods. One method compared ionization chamber measurements in the same MR-linac with and without a magnetic field (van Asselen et al 2018). The second method was based on a direct calibration of the ionization chamber in the MR-linac traceable to a water calorimetry measurement (de Prez et al 2019).

In this work, we present two different experimental methods for the determination of magnetic field correction factors for ionization chambers in parallel orientation. One method utilizes a 1.5 T electromagnet to determine the effect of the magnetic field on the ionization chamber in perpendicular orientation using a conventional linac. In a second step, the same ionization chamber is irradiated inside an MR-linac in perpendicular as well as in parallel orientation. This is done to quantify the signal change caused by repositioning the ionization chamber from the perpendicular to the parallel orientation in an MR-linac. Combining the results of both measurements, a magnetic field correction factor can be calculated for the parallel orientation.

The second method presented here is to determine the magnetic field correction for ionization chambers in parallel orientation by cross-calibration directly in the MR-linac with alanine measurements evaluated by electron paramagnetic resonance (EPR) dosimetry. A similar method was presented at an international conference before (Billas et al 2017).

The aim of this work is to determine magnetic field correction factors for different ionization chambers positioned in parallel orientation with respect to the magnetic field using those two experimental techniques.

2. Material and methods

2.1. Formalism

One way to express magnetic field correction factors was previously presented by van Asselen et al (2018).
A magnetic field correction factor $k_{\vec{B}, Q}$ was defined, that can be applied for a specific magnetic flux density $\vec{B}$ and a specific beam quality $Q$ to correct the response of an ionization chamber for the influence of the magnetic field. $k_{\vec{B}, Q}$ can be expressed as

$$k_{\vec{B}, Q} = c_{\vec{B}} k_{\vec{B}, M, Q}$$  \hspace{1cm} (1)

where $c_{\vec{B}}$ describes the change of absorbed dose to water by the magnetic field in a certain set of reference conditions:

$$c_{\vec{B}} = \frac{D_{\vec{B} = 0}}{D_{\vec{B} = \vec{M}}}. \hspace{1cm} (2)$$

$k_{\vec{B}, M, Q}$ is the ratio of the readings of an ionization chamber in the same reference conditions with and without the influence of a magnetic field:

$$k_{\vec{B}, M, Q} = \frac{M}{m}.$$  \hspace{1cm} (3)

The advantage of this formulation is that $k_{\vec{B}, M, Q}$ can be easily measured and simulated by comparing ionization chamber measurements or simulations with and without the influence of a magnetic field. In contrast, the experimental determination of $c_{\vec{B}}$ is more challenging. Currently the common approach to determining $c_{\vec{B}}$ is by Monte Carlo simulations (O’Brien et al 2016, Delfs et al 2018, Malkov and Rogers 2018, van Asselen et al 2018, Billas et al 2020). At MR-linacs, the only way to measure $c_{\vec{B}}$ is by turning off the magnetic field. For economic reasons, this is not practicable in clinical environments.

### 2.2. Electromagnet measurements in perpendicular orientation

The ionization chambers used for this part of the experiments are listed in table 1. In this experiment, the perpendicular orientation is defined as the orientation in which the Lorentz force deflects the secondary electrons towards the tip of the ionization chamber (figure 1).

For irradiation, two medical linacs (Precise Treatment System (151605 and 151617), Elekta AB, Stockholm, Sweden) have been used; the nominal accelerating voltage was set to 4, 6 and 8 MV. An in-house monitor chamber (Kapsch and Krauss 2009) was mounted on the shadow tray of the linac to monitor the accelerator’s output. A large electromagnet (ER073W, Bruker, Billerica, USA) was placed in front of the accelerator. A Hall sensor was positioned on one of the pole shoes to monitor the magnetic flux density using a digital teslameter (DTM 151, Group3 Technology Limited, Auckland, New Zealand). A 6 $\times$ 20 $\times$ 20 cm³ water phantom was placed in the 6 cm gap between the pole shoes of the magnet. The source-to-surface distance (SSD) was 110 cm. The photon beam was collimated to 4 $\times$ 10 cm² at the isocentre. The reference point of the ionization chambers was placed at a 10 cm water-equivalent depth. All measurements were repeated on three different days including a full repositioning of the detector.

The charge collected by the ionization chambers ($Q_{\text{probe}}$) and the charge collected by the transmission monitor chamber ($Q_{\text{mon}}$) were measured simultaneously using electrometers (Keithley 6517, Keithley Instruments, Solon, USA). The detectors were pre-irradiated with at least 1000 MU before each measurement; the charge was collected for 150 s Measurements were conducted for a magnetic flux density of $B = 1.5$ T. This procedure was already used in our previous work (Pojtinger et al 2019), where it had been shown to be in agreement with Monte Carlo simulations.

The charge collected by the ionization chamber was normalized to the charge collected by the transmission monitor chamber. Then, $k_{\vec{B}, M, Q}$ in perpendicular orientation was calculated by dividing this ratio measured at 0 T by the ratio at 1.5 T. In this work, the resulting quantity is called $k_{\perp, Q}$:

$$k_{\perp, Q} = \left( \frac{Q_{\text{mon}}}{Q_{\text{probe}}} \right)_{B=0\ T} / \left( \frac{Q_{\text{mon}}}{Q_{\text{probe}}} \right)_{B=1.5\ T}.$$  \hspace{1cm} (4)

$k_{\perp, Q}$ was measured for the beam qualities 4 MV, 6 MV and 8 MV ($k_{\perp, Q=4\ MV}$, $k_{\perp, Q=6\ MV}$ and $k_{\perp, Q=8\ MV}$). These results were used to demonstrate that $k_{\perp, Q}$ increases linearly with the photon beam quality specifier.

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**Table 1. Ionization chambers used in perpendicular orientation for the experimental determination of the relative response in magnetic fields.**

| Ionization chamber | Type       | S/N               | Radius (mm) | Length (mm) |
|--------------------|------------|-------------------|-------------|-------------|
| PTW 30013          | Farmer     | 006762, 009193    | 3.05        | 23          |
| PTW 31010          | Semiflex   | 0948, 03289       | 2.75        | 6.5         |
| PTW 31021          | Semiflex 3D| 141576, 141577    | 2.4         | 4.8         |

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Table 2. Ionization chambers used for the experimental determination of the influence of changing the detector’s orientation in an MR-linac setup. The dimensions of the ionization chamber’s sensitive volumes are summarized in table 1.

| Ionization chamber | Type       | S/N       |
|--------------------|------------|-----------|
| PTW 30013          | Farmer     | 006762, 010389 |
| PTW 31010          | Semiflex   | 03289, 007525 |
| PTW 31021          | Semiflex 3D| 141576, 142175 |

TPR_{20,10}, as it is defined in Andreo et al. (2006). Then, \( k_{\perp,Q=7\,\text{MV}} \) was calculated by linear interpolation between \( k_{\perp,Q=6\,\text{MV}} \) and \( k_{\perp,Q=8\,\text{MV}} \):

\[
k_{\perp,Q=7\,\text{MV}} = \frac{k_{\perp,Q=8\,\text{MV}} - k_{\perp,Q=6\,\text{MV}}}{\text{TPR}_{20,10}(7\,\text{MV}) - \text{TPR}_{20,10}(6\,\text{MV})} \cdot \left( \text{TPR}_{20,10}(6\,\text{MV}) - \text{TPR}_{20,10}(7\,\text{MV}) \right) + k_{\perp,Q=6\,\text{MV}}
\]

The values for TPR_{20,10}, for the conventional linacs have already been published in Krauss and Kapsch (2014). For the MR-linac, TPR_{20,10} was presented by de Prez et al. (2019).

2.3. Ionization chamber measurements at the MR-linac

In the second part of the experiments, the ionization chambers were irradiated using a 1.5 T MR-linac (Unity, Elekta AB, Stockholm, Sweden) in perpendicular as well as parallel orientation (see figure 1). Not all the ionization chambers listed in table 1 were available for the experiments at the MR-linac. Therefore, other ionization chambers of the same type have been included with the MR-linac measurements, to investigate intra-type variabilities. The list of ionization chambers that were used for this part of the experiment can be found in table 2.

The ionization chambers were positioned inside an MR-compatible water phantom (Beamscan MR, PTW, Freiburg, Germany). The phantom was placed at SSD = 113.15 cm and the gantry angle was set to 90°. The photon beam was collimated to \( 10 \times 10 \) cm² at the isocentre, what corresponds to a \( 7.89 \times 7.89 \) cm² square field at the SSD. The reference point of the ionization chamber was positioned at a 10 cm water-equivalent depth. Each ionization chamber was irradiated seven times with 200 MU. The collected charge was measured using an electrometer (Unidos Webline (S/N 2161), PTW, Freiburg, Germany). The series of measurements with each ionization chamber was repeated five times, including a full repositioning of the detector in the parallel as well as in the perpendicular orientation.

For the quantification of the influence of the rotation of the chamber axis around the beam direction, the relative change of the chamber response \( c_{\text{rot}} \) has been determined as the ratio of the measured charges in perpendicular (\( Q_{\perp}\)) and parallel orientation (\( Q_{\parallel}\)):

\[
c_{\text{rot}} = \frac{Q_{\perp}}{Q_{\parallel}}
\]

All charges have been corrected for the influence of water temperature and atmospheric pressure.

Then, the total influence of the magnetic field on the measurement in parallel orientation can be calculated as:

\[
k_{\parallel} = c_{\text{rot}} \cdot k_{\perp,Q=7\,\text{MV}}
\]

2.4. Magnetic field correction factors based on alanine measurements

Alanine pellets were irradiated at the 1.5 T MR-linac (Unity, Elekta AB, Sweden) using the same procedure as for the ionization chambers. For this, the alanine pellets were placed inside an inhouse manufactured holder. This holder was made of polymethyl methacrylate and had the shape of the Farmer-type ionization chamber PTW 30013. A stack of eight alanine pellets can be inserted into the tip of this holder (figure 2). The holder was built in such a way that the centre of the fourth pellet sits at the same position as the reference point of a PTW 30013 Farmer ionization chamber, i.e. 13 mm from the tip on the chamber axis. For irradiation, the holder was placed in parallel orientation with respect to the magnetic field (figure 1).

Again, the measurements were repeated five times, including a full repositioning of the alanine holder.

The procedure for evaluating the applied dose on the alanine pellets was previously described in detail elsewhere (Anton 2005, 2006).

To determine the dose distribution perpendicular to the beam axis, the beam profile across the detector length was determined from the readings of the eight alanine pellets contained in the holder in a first step. This was done for all five measurements. After that, the average beam profile was fitted with a cubic
polynomial by polynomial regression (see figure 5). The maximum of this function was used to approximate the absorbed dose to water in the centre of the beam and was noted as $D_{\text{alanine}}$.

For all ionization chambers in table 3, a cobalt-60 calibration factor ($N$) was determined traceable to the German primary standard of absorbed dose to water at the National Metrology Institute (PTB, Germany). In addition, corrections for the polarity effect ($k_p$) and ion recombination ($k_s$) were determined experimentally at the MR-linac. Values for the beam quality correction factor ($k_Q$) have been taken from Andreo et al (2020).

The influence of the magnetic field on the depth dose distribution in water ($c_B$) was calculated using the Monte Carlo system EGSnrc (Kawrakow et al 2019). For this, a full accelerator head model of the Elekta Unity was modeled in BEAMnrc (Rogers et al 2018). A detailed description and benchmark of the accelerator head model can be found in Friedel et al (2019). The accelerator head model was compiled as a shared library and coupled to the EGSnrc usercode egs_chamber (Wulff et al 2008). Simulation parameters were set in accordance with earlier simulations (Pojtinger et al 2018, 2019). The dose was scored for a water cylinder placed at a 10 cm depth inside a 30 x 30 x 30 cm$^3$ water phantom. The radius of the water cylinder was set to 1 mm and the thickness was set to 0.2 mm. The irradiation conditions were set in accordance to the MR-linac measurements.

A correction for the volume averaging effect ($k_V$) was calculated as described in IAEA TRS-483 (IAEA 2017), by folding the beam profile resulting from the alanine measurements with the ionization chamber’s cross-sectional area.

The influence of a magnetic field on measurements using alanine was recently investigated by Billas et al (2020). To compensate for this effects, Billas et al (2020) introduced an alanine quality correction factor $k_{a,B,Q}$. For this work, $k_{a,B,Q}$ was determined experimentally, what will be discussed later.

With the correction for the temperature and pressure ($k_t$), the dose to water measured with an ionization chamber ($D_{IC}$) can be calculated from the reading of an ionization chamber ($M_{probe}$) as:

$$D_{IC} = N \cdot k_Q \cdot k_p \cdot k_{probe} \cdot k_B \cdot k_M \cdot c_B \cdot k_{B,M,Q} = 1.5 \text{ T}.$$  

(8)

The quantities that are written inside brackets have been determined directly in the measurement situation, at $B = 1.5 \text{ T}$. If the dose to water is measured with an ionization chamber as well as with alanine for the same irradiation conditions, $D_{IC}$ can be replaced by $D_{\text{alanine}}$:

$$D_{\text{ alanine}} = N \cdot k_Q \cdot k_{a,B,Q} \cdot M_{probe} \cdot k_p \cdot k_s \cdot k_V \cdot c_B \cdot k_{B,M,Q}.$$  

(9)

This equation can be solved for $k_{B,M,Q}$. Hence, it can be used for the determination of $k_{B,M,Q}$, based on an alanine measurement. To make it clear that this equation is based on an alanine measurement, in the context of this equation is noted as $k_{\text{alanine}}$:

$$k_{\text{alanine}} = \frac{D_{\text{alanine}}}{N \cdot k_Q \cdot k_{a,B,Q} \cdot M_{probe} \cdot k_p \cdot k_s \cdot k_V \cdot c_B} = 1.5 \text{ T}.$$  

(10)
Table 4. Resulting uncertainties based on the uncertainty budget for the determination of \( k_{\text{alanine}} \).

| Quantity \( X_i \)                        | \( u(X_i) / X_i \) |
|------------------------------------------|---------------------|
| Measurement ionization chamber           | 0.19%               |
| Calculation of absolute dose IC          | 0.72%               |
| Calculation of absolute dose alanine     | 0.31%               |
| Relative combined standard uncertainty   | 0.80%               |

2.5. Magnetic field correction factors for alanine

To investigate the influence of the magnetic field on the alanine measurements, \( k_{\text{al}, \perp, Q} \) was directly measured at the 1.5 T MR-linac (Unity, Elekta AB, Sweden) located at the Hôpital Riviera-Chablais (Blonay, Switzerland). At this site it was possible to perform measurements while the magnetic field of the MR-linac was turned off.

Alanine pellets were placed in the alanine holder that was described before and were irradiated for approximately 4700 MU. For this, the alanine holder was positioned in the isocentre of the MR-linac in 10 cm water-equivalent depth, inside of a dedicated water phantom built by the National Physical Laboratory (NPL, Teddington, England). This was repeated three times on two different days, including a full repositioning of the alanine holder. After ramping the magnetic field, the measurements were repeated.

In Billas et al (2020) the authors quantify the alanine quality correction factor for the presence of a magnetic field as:

\[
k_{\text{al}, \perp, Q} = \frac{\sigma_{\text{al}, Q}^2}{\sigma_{\text{al}, Q}^2} \cdot \frac{M_{\text{al}, Q}^2}{M_{\text{al}, Q}^2} = c_B \cdot \frac{M_{\text{al}, Q}^2}{M_{\text{al}, Q}^2} \quad (11)
\]

In this, \( M_{\text{al}, Q} \) is the alanine EPR signal for the alanine pellets irradiated without the influence of a magnetic field and \( M_{\text{al}, Q}^2 \) for the pellets irradiated under the influence of a magnetic field. \( k_{\text{al}, \perp, Q} \) was calculated based on the described measurements.

2.6. Calculation of uncertainties

Uncertainties given for \( k_{\perp, Q} \) and \( c_{\text{rot}} \) have been estimated by the standard error of the mean (SEM) (ICGM 2008). The uncertainty for \( k_{\perp, Q} \) results from the propagation of the uncertainty of \( k_{\perp, Q=7 \text{MV}} \) and \( c_{\text{rot}} \). All these values result from relative measurements that were repeated five times.

The uncertainty for \( k_{\text{alanine}} \) was calculated based on a full uncertainty budget. The uncertainties for \( N, k_p, k_Q \) and \( k_{\perp} \) are given in table 7. The uncertainty for \( c_B \) includes the Monte Carlo variance as well as an additional uncertainty of 0.2%, considering the possibility of systematic Monte Carlo uncertainties (Wulff et al 2010). Uncertainties for temperature and atmospheric pressure measurements were calculated based on information given by the manufacturer of the measuring instruments. Additional uncertainties were included for positioning, the electrometer as well as the dose values obtained by alanine dosimetry.

The uncertainty budget for the absorbed dose to water based on an individual alanine measurement was described in detail in the literature (Anton 2006). In this work, the determination of the uncertainty for \( D_{\text{alanine}} \) was divided into two intermediate steps. In a first step, the uncertainty of the mean dose measured at each pellet position was calculated by propagation of the uncertainty, based on the five individual measurements. In a second step, the uncertainty for \( D_{\text{alanine}} \) was calculated by applying propagation of the uncertainty to the polynomial regression that was applied to the mean dose values. A brief overview of the uncertainty budget is given in table 4.

For the calculation of the uncertainty of alanine correction factor \( k_{\text{al}, \perp, Q} \) propagation of uncertainty was applied to the uncertainty of \( c_B \) and the alanine EPR signal described by Anton (2006).

3. Results

3.1. Magnetic field correction factors for parallel orientations

Figure 5 shows the results of the linear regression for \( k_{\perp, Q} \) over TPR\(_{20,10}\). All linear regressions resulted in a coefficient of determination of \( R^2 > 0.99 \).

The results for \( k_{\perp, Q=7 \text{MV}} \) are shown in table 5.

The Farmer ionization chamber PTW 30013, which has the largest volume among the investigated thimble-type chambers, showed a 2.9% increase in response in the magnetic field. Comparing the different chambers of the same type, the two PTW 30013 ionization chambers show a very small variability in \( k_{\perp, Q=7 \text{MV}} \), which is below 0.1%.
Figure 3. Linear regression of $k_\perp, Q$ for different beam qualities. The red dashed lines show the results of the linear regressions.

Table 5. Experimental values for $k_\perp, Q=7\text{MV}$ and $k_{\vec{B}, Q}$, for the measurements in perpendicular orientation (figure 1).

| Detector       | S/N          | $k_\perp, Q=7\text{MV}$ | $k_\perp, Q=7\text{MV} \cdot c_{\vec{B}} = k_{\vec{B}, Q}$ |
|----------------|--------------|--------------------------|-------------------------------------------------|
| PTW 30013      | 006762       | 0.97140 (95)             | 0.9652 (22)                                     |
| PTW 30013      | 009193       | 0.9720 (11)              | 0.9658 (22)                                     |
| PTW 31010      | 0948         | 1.0179 (22)              | 1.0114 (30)                                     |
| PTW 31010      | 03289        | 1.0208 (22)              | 1.0142 (30)                                     |
| PTW 31021      | 141576       | 1.0546 (18)              | 1.0478 (28)                                     |
| PTW 31021      | 141577       | 1.0608 (17)              | 1.0540 (27)                                     |

Table 6. Experimental values for $c_{\text{rot}}$ and $k_{||}$.

| Detector       | S/N          | $c_{\text{rot}}$ | $k_{||}$ | $k_3 \cdot c_{\vec{B}} = k_{\vec{B}, Q}$ |
|----------------|--------------|------------------|---------|----------------------------------------|
| PTW 30013      | 006762       | 1.02840(38)      | 0.9990 (10) | 0.9926 (22)                         |
| PTW 30013      | 010389       | 1.02889(57)      | 0.9999 (23) | 0.9935 (31)                         |
| PTW 31010      | 03289        | 0.97952(90)      | 0.97661 (66) | 0.9841 (27)                         |
| PTW 31021      | 141576       | 0.93914(61)      | 0.94076 (75) | 0.9841 (27)                         |

A mean reduction of the response amounting to 1.9% was observed for the smaller PTW 31010 ionization chamber. This is only a minor effect compared to the increase seen for the PTW 30013. Furthermore, the variability in $k_\perp, Q=7\text{MV}$ is about 0.3% for this orientation.

The smallest ionization chamber (PTW 31021) followed this trend with a further decrease of the response by more than 5.8%. $k_\perp, Q$, differed by more than 0.6% for the two ionization chambers under investigation, for all beam qualities between 4 MV and 8 MV (see figure 3).

3.1.1. Magnetic field correction factors in parallel orientation

Figure 4 shows measured signals $M_{\text{probe}}$ corrected for temperature and atmospheric pressure for all ionization chamber measurements conducted in the MR-linac. The values were normalized to the average value over all measurements using the same ionization chamber, in the same orientation $M_{\text{probe}}$. The distribution of $M_{\text{probe}} / M_{\text{probe}}$ can be interpreted as a quantification of the experimental reproducibility. All values are within 0.3%, for both orientations and all ionization chambers.

The values for $c_{\text{rot}}$ and $k_{||}$ are shown in table 6. The change of the orientation of the Farmer ionization chamber PTW 30013 from parallel to perpendicular increased the response by 2.9%. Again, the opposite effect was observed for the smaller ionization chambers PTW 31010 and PTW 31021. For the PTW 31010 the response decreases by about 2.1% and for the PTW 31021 by 6.0%. No significant intra-type variations for the ionization chambers used were observed. Tables 5 and 6 also include values for $k_{\vec{B}, Q}$. For this $k_{\perp, Q=7\text{MV}}$ was multiplied with the same $c_{\vec{B}}$ that was calculated by Monte Carlo for the determination of $k_{\text{alanine}}$.

The total influence of the magnetic field on the response of the ionization chambers was between 0.7% and 1.6% for the parallel orientation.
3.2. Magnetic field correction factors based on alanine measurements

Figure 5 shows the beam profile acquired with the alanine measurements. The maximum dose per MU was found between the position of the third and fourth alanine pellet as $D_{\text{max}} = 0.01366 \text{ Gy MU}^{-1}$.

The values for all correction factors can be found in table 7. The most prominent correction was the correction for the beam quality $k_Q$, whereas $k_{\text{alanine}}$ (see equation (10)) quantifies the total influence of the magnetic field on the signal of the ionization chamber.

The simulation of the influence of the magnetic field on the dose resulted in $c_B = 0.9936(20)$.

3.3. Magnetic field correction factors for alanine

The direct measurement of the alanine quality correction factor for the presence of a magnetic field ($k_{\text{al},B,Q}$) resulted in $k_{\text{al},B,Q} = 1.0010(28)$ and $k_{\text{al},B,Q} = 0.9989(28)$ for the parallel and perpendicular orientation, respectively. The results for the parallel orientation was used for the determination of $k_{\text{alanine}}$. 
gives an impression about the accuracy (and precision) of the positioning. The maximum of the
for the ionization chamber PTW 30013 are in agreement with the measurements of de Prez
chamber PTW 30013. All values agree within the given uncertainty. In addition, all values presented for
Nevertheless, it must be mentioned that the uncertainty for
alanine holder, this could be the reason for the observed discrepancy.
that the alanine quality correction factor for the presence of a magnetic field might depend on the used
factors. In perpendicular orientations, the response of ionization chambers is increased for thimble-type
sensitive volume but differ in length (table 7). Therefore, some assumptions can be derived from results, for
the influence of the length of the sensitive volume of ionization chambers on magnetic field correction
factors. In perpendicular orientations, the response of ionization chambers is increased for thimble-type
ionization chambers with a long sensitive volume (like Farmer type ionization chambers). For short
ionization chambers, the response is more likely to be decreased instead of increased. Also, short ionization
chambers show a higher variability in $k_{B,Q}$. The measurements involving the two PTW 31021 ionization
chambers show a variability in $k_{B,Q}$ of more than 0.6%.

| Detector | PTW 30013 | PTW 31010 | PTW 31021 |
|----------|-----------|-----------|-----------|
| S/N      | 0.9976(12)| 1.0000(11)| 0.9965(12)|
| $k_p$    | 0.9856(62)| 0.9845(62)| 0.9865(62)|
| $k_Q$    | 1.0056(51)| 1.0036(51)| 1.0043(51)|
| $k_T$    | 1.0033(10)| 1.0003(10)| 1.0002(10)|
| N ($\mu$Gy C$^{-1}$) | 0.5384(14) | 2.9350(74) | 5.776(15) |
| $k_{\text{alanine}}$ | 0.9965(80) | 1.0019(80) | 0.9949(80) |
| $k_{\text{alanine}c_{\bar{B}} = k_{\bar{B},Q}}$ | 0.9901(72) | 0.9955(72) | 0.9885(71) |

4. Discussion

This work utilized alanine dosimetry as well as high precision measurements inside an electromagnet in a
conventional linac for the determination of magnetic field correction factors $k_{\bar{B},Q}$ for several ionization
chambers. $k_{\bar{B},Q}$ was measured for the parallel ionization chamber orientation (figure 1). This was done for
Farmer type as well as for small volume ionization chambers. For this purpose, two independent methods
were presented and described in detail.

Several parameters presented in this work quantify the reproducibility of the proposed methods. The results
based on measurements in the electromagnet showed an SEM below 0.3% for all measurements. This
was already shown for other magnetic flux densities in a previous publication (Poijingter et al 2019). To
quantify the reproducibility of the experiments at the MR-linac, we have determined the ratio $M_{\text{probe}}/M_{\text{probe}}$.
As the measurements at the MR-linac were carried out on three different days, this value gives a
representative impression of the stability of the internal monitor chamber. $M_{\text{probe}}/M_{\text{probe}}$ was shown to vary
by at most ±0.3% for all measurements, proving a high level of repeatability and reproducibility.

Figure 4 gives an impression about the accuracy (and precision) of the positioning. The maximum of the
alanine beam profile has an offset of 1 mm to the fourth alanine pellet. As the alanine holder is designed like
a Farmer-type ionization chamber and was positioned in the same way as the ionization chambers, it can be
speculated, that there was an offset in the in-bore direction of approximately 1 mm during the ionization
chamber measurement.

In contrast to the work of Billas et al (2020) our investigations show, that measurements based on alanine
dosimetry are not influenced by a 1.5 T magnetic field for a 7 MV beam quality. Billas et al (2020) reported
that the alanine quality correction factor for the presence of a magnetic field might depend on the used
alanine holder, this could be the reason for the observed discrepancy.

$k_{||}$ can be directly compared to $k_{\text{alanine}}$. All presented values agree within the estimated uncertainties.
Nevertheless, it must be mentioned that the uncertainty for $k_{\text{alanine}}$ is large (0.80%). As shown in table 7, the
highest contribution to the total uncertainty value is introduced by the correction for the beam quality.
Anyway, this uncertainty is still comparable to the uncertainties of the values that are currently available in
literature that in many cases are not based on a full uncertainty budget.

Recently, van Asselen et al (2018) have also determined values for $k_{\bar{B},Q}$, for the Farmer ionization
chamber PTW 30013. All values agree within the given uncertainty. In addition, all values presented for $k_{\bar{B},Q}$
for the ionization chamber PTW 30013 are in agreement with the measurements of de Prez et al (2019).

Furthermore, this work confirms the value of $c_{\bar{B}}$ that was calculated by van Asselen et al (2018). van
Asselen et al (2018) have used the treatment planning software for the determination of $c_{\bar{B}}$. This work
confirms the published value using the more accurate Monte Carlo algorithm implemented in EGStarc. The
value presented in this work also agrees with the value calculated by O’Brien et al (2016), which was
calculated using Geant4.

All ionization chambers that were used for the experiments in this study have a similar radius of the
sensitive volume but differ in length (table 1). Therefore, some assumptions can be derived from results, for
the influence of the length of the sensitive volume of ionization chambers on magnetic field correction
factors. In perpendicular orientations, the response of ionization chambers is increased for thimble-type
ionization chambers with a long sensitive volume (like Farmer type ionization chambers). For short
ionization chambers, the response is more likely to be decreased instead of increased. Also, short ionization
chambers show a higher variability in $k_{B,Q}$. The measurements involving the two PTW 31021 ionization
chambers show a variability in $k_{B,Q}$ of more than 0.6%.
5. Conclusion

Two methods for the determination of magnetic field correction factors for ionization chambers for parallel and perpendicular orientations have been presented. One method is based on alanine dosimetry, the other method combines measurements inside an electromagnet with measurements inside an MR-linac. Both methods showed an excellent reproducibility and are thus suited for clinical usage in MR-guided radiotherapy.

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