Direct measurement of ion chamber correction factors, $k_Q$ and $k_B$, in a 7 MV MRI-linac

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Abstract

The output of MRI-integrated photon therapy (MRgXT) devices is measured in terms of absorbed dose to water, $D_w$. Traditionally this is done with reference type ion chambers calibrated in a beam quality $Q_0$ without magnetic field. To correct the ion chamber response for the application in the magnetic field, a factor needs to be applied that corrects for both beam quality $Q$ and the presence of the magnetic field $B$, $k_{Q,B}$. This can be expressed as the product of $k_Q$, without magnetic field, and ion chamber magnetic field correction, $k_B$. $k_B$ depends on the magnetic field strength and its direction, the direction of the beam and the orientation and type of the ion chamber. In this study, for the first time, both $k_Q$ and $k_B$ were measured directly for six waterproof ion chambers ($3 \times$ PTW 30013 and $3 \times$ IBA FC65-G) in a pre-clinical 7 MV MRI-linac at 0 T and at 1.5 T. Measurements were done with the only available primary standard built for this purpose, a water calorimeter. Resulting $k_Q$ factors for PTW and IBA chambers were 0.985(5) and 0.990(4), respectively. $k_B$ factors were measured with the chambers in antiparallel direction to the magnetic field ($|| 180^\circ$), and perpendicular direction ($\perp$ $-90^\circ$). $k_{B||}$ and $k_{B\perp}$ for the PTW chambers were 0.985(6) and 0.963(4), respectively and for IBA chambers 0.995(4) and 0.956(4). Agreement with the available literature values was shown, partly caused by the relatively large standard deviation (SD) in those values. The values in this study are currently the only available measured values for $k_Q$ and $k_B$ in an MRI-linac that are directly linked to the international traceability framework for the quantity absorbed dose to water, $D_w$.

1. Introduction

MRI guided radiotherapy (MRgRT) uses an MRI scanner integrated with a treatment machine and allows for unprecedented real-time visualization and motion tracking of the target during the actual treatment, in real time. Several, integrated MRgRT devices are under development or in clinical use (Fallone 2014, Keall et al 2014, Mutic and Dempsey 2014, Raaymakers et al 2017). However, dosimetry in the presence of a magnetic field, $B$, is not trivial. The energy deposition of the secondary electrons trajectories is influenced by the Lorentz force and dose distributions change e.g. in build-up and penumbra regions, with depth and in regions with material and density inhomogeneities (Raaymakers et al 2004, Raaijmakers et al 2008, Oborn et al 2010, Woodings et al 2018). Traditionally, photon beams in radiotherapy are calibrated in terms of absorbed dose to water, $D_w$ by ion chambers calibrated in beam quality $Q_0$ (usually $^{60}$Co), $N_{D,Q_0}$, without magnetic field (Andreo et al 2000, Aalbers et al 2008, McEwen et al 2014). The most fundamental and direct method to calibrate detectors for reference dosimetry is against a primary standard$^3$ that realizes the unit Gray (Gy) for absorbed dose, magnetic field, and density inhomogeneities (Raaymakers et al 2008, Oborn et al 2010, Woodings et al 2018). Traditionally, photon beams in radiotherapy are calibrated in terms of absorbed dose to water, $D_w$ by ion chambers calibrated in beam quality $Q_0$ (usually $^{60}$Co), $N_{D,Q_0}$, without magnetic field (Andreo et al 2000, Aalbers et al 2008, McEwen et al 2014). The most fundamental and direct method to calibrate detectors for reference dosimetry is against a primary standard$^3$ that realizes the unit Gray (Gy) for absorbed dose, magnetic field, and density inhomogeneities (Raaymakers et al 2008, Oborn et al 2010, Woodings et al 2018). Traditionally, photon beams in radiotherapy are calibrated in terms of absorbed dose to water, $D_w$ by ion chambers calibrated in beam quality $Q_0$ (usually $^{60}$Co), $N_{D,Q_0}$, without magnetic field (Andreo et al 2000, Aalbers et al 2008, McEwen et al 2014). The most fundamental and direct method to calibrate detectors for reference dosimetry is against a primary standard$^3$ that realizes the unit Gray (Gy) for absorbed dose, magnetic field, and density inhomogeneities (Raaymakers et al 2008, Oborn et al 2010, Woodings et al 2018).

$^3$A primary standard is defined as a measurement standard obtaining a measurement result without relation to a measurement standard for a quantity of the same kind (OIML 2007).
Reference dosimetry in MRI-integrated photon therapy (MRgXT) devices is done with ion chambers that are placed in the magnetic field of an MRI-linac. Therefore, the change in ion chamber response needs to be corrected for both beam quality, \( Q \), and magnetic field, \( B \), by a factor \( k_{Q,B} \). \( D_w \) is determined according to:

\[
N_{D_w} = \frac{D_w}{M}. 
\]  

(1)

The correction factor \( k_{Q,B} \), in analogy to \( k_Q \) (Andreo 1992), defined as the ratio between its calibration coefficients in beam quality \( Q \) with magnetic field, \( N_{D_w,Q,B} \), and that in reference beam quality \( Q_0 \) without magnetic field, \( N_{D_w,Q_0} \):

\[
k_{Q,B} = \frac{N_{D_w,Q,B}}{N_{D_w,Q_0}}. 
\]  

(2)

Another approach is to apply the product of two independent correction factors, i.e. a beam quality correction for the MRI-linac photon beam without magnetic field, \( k_Q \), and a magnetic field correction \( k_B \):

\[
k_{Q,B} = k_Q \cdot k_B = \frac{N_{D_w,Q}}{N_{D_w,Q_0}} \cdot \frac{N_{D_w,Q,B}}{N_{D_w,Q}}. 
\]  

(3)

Monte Carlo calculations and measurements showed that the magnetic field affects \( k_B \) by several percent (Meijsing et al 2009, Reynolds et al 2013, Smit et al 2013). The amount depends on ion chamber design and construction, its orientation in the field and the direction and magnitude of the magnetic field in relation to the radiation beam. Recent studies reported \( k_B \) factors, determined either by Monte Carlo calculations (O’Brien et al 2016, Spindeldreier et al 2017, Malkov and Rogers 2018, Pojtinger et al 2018) or by measurement of ion chamber readings with and without magnetic field (van Asselen et al 2016, Spindeldreier 2017, Malkov and Rogers 2018, Pojtinger et al 2018) or by measurement of ion chamber readings with and without magnetic field (van Asselen et al 2018). Most of these studies assumed that \( k_Q \) in equation (4) can be taken from existing Codes of Practice, CoPs (Andreo et al 2000, Aalbers et al 2008, McEwen et al 2014). However, as shown by Woodings et al (2018), in case of the Elekta Unity MRI-linac used in this study, the flattening filter free (FFF) beam characteristics are affected by the MRI-cryostat wall. Consequently, the applicability of the \( k_Q \) from existing CoPs for application in MRI-linacs was never confirmed. In addition, despite the recommendation to measure \( k_Q \) against primary standards (Andreo et al 2000), which presumably also holds for \( k_B \), no experimental data for \( k_Q \) or \( k_B \) based on primary standards in MRI-linacs is available. In order to do this, ion chambers need to be calibrated in beam quality \( Q_0 \) (60Co) without magnetic field to obtain \( N_{D_w,Q_0} \), and in MRI-linac beam quality \( Q \) both with and without magnetic field to obtain respectively \( N_{D_w,Q,B} \) and \( N_{D_w,Q} \) in equation (4).

VSL developed a new water calorimeter as a primary standard for absorbed dose to water in 60Co, kV and MV photon beams. It was designed to operate in a magnetic field of MRI incorporated treatment devices (de Prez et al 2016a). The calorimeter demonstrated its capability for on-site measurements in conventional flattened (cFF) and FFF high-energy photon beams (de Prez et al 2018b). Its international agreement for measurement of \( D_w \) in MV and 60Co photon beams without magnetic field (i.e. at 0 T) and its uncertainty was confirmed by BIPM4 key-comparisons (Picard et al 2017, Kessler et al 2018). A preliminary study showed its feasibility to measure absorbed dose to water, \( D_w \), in a magnetic field and to calibrate ion chambers directly in the calorimeter phantom (de Prez et al 2016b). A more comprehensive study confirmed that the uncertainty for measurement of \( D_w \) with a water calorimeter in a 1.5 T magnetic field is estimated to be the same as under conventional reference conditions (de Prez et al 2019). The VSL water calorimeter is currently the only primary standard operable in a magnetic field that provides a direct link to the international system of units (SI).

The aim of this study is to measure \( k_Q \) and \( k_B \) directly for two ion chamber types of each three serial numbers in a pre-clinical 7 MV Elekta Unity MRI-linac at 0 T and at 1.5 T. This is done by direct \( D_w \) calibrations against the VSL primary standard in 60Co, without magnetic field, and in beam quality \( Q \), with and without magnetic field. Some of the materials and methods applied here, were described in detail earlier (de Prez et al 2016a, 2018a, 2019).

2. Materials and methods

2.1. The wide bore hybrid MRI-linac system

The pre-clinical Elekta Unity hybrid MRI-linac system comprised a modified 1.5 T Philips wide bore MRI with 70 cm diameter and an Elekta 7 MV standing wave linear accelerator producing an FFF photon beam with a pulse

\(^4\)The Bureau Internationales des Poids et Mesures, BIPM in Sèvres, is an international organization established by the Metre Convention, through which Member States act together on matters related to measurement science and measurement standards (www.bipm.org).
rate frequency (PRF) of 275 Hz (Raaymakers et al 2009, Lagendijk et al 2014, Woodings et al 2018). A ring around the patient bore allowed for rotation with the accelerator iso-centre at 143.5 cm. It provided for a transverse magnetic field relative to the direction of the MV photon beam. The linac was equipped with an electronic portal imaging device (EPID), used for alignment of measurement equipment. The beam quality expressed in TPR_{20,10} had a value of 0.701(2), independent of the presence of the magnetic field within its reported standard uncertainty (van Asselen et al 2018). All measurements in the current study were performed with a vertical beam, i.e. at gantry angle 0°.

2.2. The orientation dependence of $k_{Q,B}$

The effect on ion chamber responses due to the magnetic field, $B$, in beam quality $Q$, $k_{Q,B}$ in equation (4), is dependent on the orientation of the chamber and the direction of the magnetic field in relation to that of the beam. Hence, these conditions need to be specified to fully describe the relevant measurement conditions. It was shown previously that chamber orientations with the thimble facing in opposite direction (or the magnetic field sign changed) can result in a different chamber response. This is caused by a non-symmetric, chamber dependent dead-volume near the chamber guard electrode, i.e. at the stem-side (Butler et al 2015, Malkov and Rogers 2017, Spindeldreier et al 2017). It is caused by the design of modern ion chambers. The orientations applied in this study are illustrated in figure 1.

2.3. Calorimetric determination of $D_w$

The $D_w$ measurements are described elsewhere (de Prez et al 2019). Measurements at 1.5 T took place on day, 1, 2, 3 and 19 of a 19 d period (six measurement series). The MRI-linac magnet was ramped down on day 22 and calorimeter measurements were repeated at 0 T on day 23, 24, and 34 (three measurement series). The measurements were performed in groups of approximately $N = 30$ consecutive calorimeter runs, taking about 5 min per run of which 1 min of irradiation. On three occasions, two with magnetic field and one without magnetic field, the orientation of the calorimeter high-purity water cell was changed from perpendicular to parallel as described previously (de Prez et al 2019). Each time this was done on the same day. It was shown earlier that the calorimeter performance, both with and without magnetic field, was unaffected by the orientation of the vessel. Therefore, in this study, perpendicular and parallel measurements with magnetic field were combined for their contribution to $D_w$. The same was done for perpendicular and parallel measurement without magnetic field.

2.4. Ion chamber calibration

Ion chamber calibrations at 1.5 T were done in the period between day 4 and day 18 and at 0 T in the period between day 25 and day 33, both preceded and succeeded by calorimeter $D_w$ measurements. Prior to the ion chamber calibration, all chambers were imaged by CT and no irregularities in chamber construction were observed. The ion chamber signal, $M$, was integrated over 60 s, the same integration time as used for the calorimetric $D_w$ measurements, described earlier (de Prez et al 2019). This was done to avoid introduction of differences in beam on-off timing between calorimetry and ion chamber measurements. Furthermore, the ion chambers signal was measured in the same set-up as the $D_w$ measurements, i.e. inside the calorimeter water phantom, however, with the water at room temperature. The corrected ion chamber reading, $M$, in equation (1) was determined by:

$$M = (M_{\text{raw}} - M_{\text{leakage}}) \cdot k_{\text{elec}} \cdot k_{p,T} \cdot k_s \cdot k_{\text{pol}} \cdot k_R,$$

where the leakage signal, $M_{\text{leakage}}$, in the electrometer readings, $M_{\text{raw}}$, was shown to be negligible ($<0.05\%$). The reading was corrected for electrometer calibration, $k_{\text{elec}}$, air cavity density compared to reference air density, $k_{p,T}$, incomplete charge collection due to recombination, $k_s$, and chamber polarity, $k_{\text{pol}}$. Temperature was measured in
water, close to the ion chamber thimble. The air pressure was measured in the linac room at the approximate ion chamber height. Deviation from geometrical reference conditions and to the dose at the central axis of the beam was corrected for by $k_d$:

$$k_R = k_{\text{SDD}} \cdot k_d \cdot k_v,$$

(6)

which contains corrections to reference source detector distance (SDD), $k_{\text{SDD}}$, specific depth (in g cm$^{-2}$) in water, $k_d$, and correction for volume averaging over the length of the ion chamber cavity, $k_v$.

The ion chamber collecting potential, supplied to the central electrode by the electrometer (Keithley 6517B), was set to $-300$ V. In the MRI-linac, the ion recombination correction, $k_v$, was measured by applying the method described by Weinhouss and Melli (1984) as recommended by commonly used Codes of Practice (Andreo et al 2000) with a collecting potential of $-100$ V directly following a measurement with a collection potential of $-300$ V. This method was shown to be independent of magnetic field (Smit et al 2013). In the beam quality $Q_0$, $^{60}$Co, the ion recombination was measured by applying the method described by Boutillon (1998) for continuous beams. For all beams, the polarity correction, $k_{\text{pol}}$, was applied according to the methods described by e.g. Andreo et al (2000), performing measurements at $+300$ V collecting potential.

No additional correction was applied for the air attenuation between the monitor ion chamber and the calorimeter, since the variation of the correction with varying ambient conditions was small. No correction was applied for air relative humidity since all measurements took place at a relative humidity between 25% and 60% for which no correction is needed (Bichsel et al 1979, McEwen and Taank 2017). SDD of the instruments, i.e. ion chambers and calorimeter, was within 0.2 cm from the nominal SDD of 139.3 cm, 4.2 cm above iso-centre. The depth of the instruments was within 0.06 g cm$^{-2}$ from the nominal value of 10 g cm$^{-2}$. SDD and depth were corrected to the nominal values by inverse square law and effective attenuation, $\mu (0.036$ cm$^2$ g$^{-1}$ based on a TPR$_{20,0}$ of 0.70), as described by Andreo et al (2017), respectively $k_{\text{SDD}}$ and $k_d$ in equation (6). The field size of the beam was set to $10 \times 10$ cm$^2$ at the iso-centre, corresponding to $9.7 \times 9.7$ cm$^2$ at the measurement position. The correction to the central axis-profile was applied by the ion chamber volume averaging correction, $k_v$, by a simple integration of the lateral beam profile over the length of the ion chamber cavity and normalization to central axis dose as described by Palmans et al (2017). In this study $k_v$ was applied separately and not included in $k_d$ because the available $Q_0$ literature value to compare to was also determined without inclusion of $k_v$ (Malkov and Rogers 2018).

The ion chambers were calibrated in both antiparallel (|| 180$^\circ$) and perpendicular (⊥ −90$^\circ$) direction in a 1.5 T magnetic field, illustrated in figure 1. After ramp down, the calibrations were repeated at 0 T.

### 2.5. Ion chamber positioning

The ion chambers were positioned inside the calorimeter phantom by methods described elsewhere (de Prez et al 2016a). To prevent variations in reading due to air around the ion chamber waterproofing sleeves (Hackett et al 2016), all measurements were performed directly in water using waterproof ion chambers. The black line on the stem of the ion chambers was facing the radiation source. After measurement in perpendicular orientation (figure 1(B), ⊥ −90$^\circ$), the ion chambers orientations were remotely rotated 90$^\circ$ around the beam-axis to antiparallel orientation (figure 1(A), || 180$^\circ$) without the need to access the water phantom. The difference between SDD in both orientations was negligible (<0.05 mm). The difference in ion chamber SDD, compared to calorimeter SDD, was measured with an uncertainty of 0.3 mm ($k = 1$), equivalent to a relative standard uncertainty of 0.05% on the determination of $k_{\text{SDD}}$ in equation (6). This was slightly larger than in conventional linacs where it was considered to be 0.02% (de Prez et al 2016a). The uncertainties in the depth and volume averaging correction, $k_d$ and $k_v$, was the same as reported earlier (de Prez et al 2016a, 2018b), respectively 0.04% and 0.05% ($k = 1$).

### 2.6. Beam output monitoring

The $D_w$ and ion chamber measurements performed in this study took place over a period of several weeks. Therefore, an independent beam output monitor was used to normalize the measurement of $D_w$ and $M$ for determination of $N_{D_w,Q,B}$ and, after ramp-down $N_{D_w,Q}$ in equation (4). The monitor system was described in detail earlier (de Prez et al 2019), where an additional standard uncertainty of 0.16% was applied for the monitor day-to-day variations.

### 2.7. Consistency check by independent posterior cross-calibration

The ion chamber measurements in the calorimeter water phantom are potentially sensitive to errors that can be made due to e.g. unnoticed geometrical misalignment, displacement of the transmission monitor, air-bubbles around the chamber or other unwanted effects. To validate ion chamber measurement in the calorimeter, an independent consistency check was done by cross-calibrating the ion chambers in an independent experiment. This was done after the calorimeter set-up was removed from the bore and the patient couch was re-installed. Each ion chamber was cross-calibrated against the other five. The cross-calibration was performed in such a way
that most of the correction factors from equations (5) and (6) canceled. The cross-calibrations were performed at 0 T and, after magnet ramp-up, at 1.5 T in the orientations shown in figure 1, i.e. antiparallel (|| 180°) and perpendicular (\(\perp -90°\)). Measurements were performed in a modified MRI-compatible PTW MP1 water phantom, placed on the patient couch. The chambers were positioned at the iso-centre (143.5 cm), at a nominal depth of 10 cm. The black line on the stem of the ion chamber was facing the radiation source. At the same depth, approximately 2 cm off-centre, a waterproof IBA CC13 ion chamber was used as an independent monitor chamber. The ion chambers were connected to PTW Unidos E electrometers. All ion chamber readings were recorded in the same set-up. For each ion chamber, \(j\), the calibration coefficient, \(N_{D_{w}}^{cross,j}\), was determined according to:

\[
N_{D_{w}}^{cross,j} = \frac{1}{5} \sum_{i \neq j} \left( \frac{N_{D_{w}}^{\text{raw},i}}{D_{w} \cdot k_{i,j} \cdot k_{\text{pol},i}} \right) \cdot M_{i} \cdot k_{e,i} \cdot k_{\text{pol},i}.
\]

The average of absorbed dose, \(D_{w}\), based on measurement with the other five chambers \((i \neq j)\) was based on their calibration coefficients measured in the water calorimeter, \(N_{D_{w}}^{\text{raw},i}\), and represented by one fifth of the value of the numerator of the right-hand side of equation (7). Leakage signal, \(M_{\text{leakage}}\), in the electrometer readings, \(M_{\text{cross}}\), according to equation (5) was shown to be negligible (<0.05%). Corrections for polarity, \(k_{\text{pol}}\), and recombination, \(k_{r}\), were applied according to the methods described earlier. The corrections for \(k_{p,T}\) in equation (5) and \(k_{SDD}\) in equation (6) were not considered relevant because the monitor ion chamber was in a fixed geometry and therefore affected in the same way by variations in temperature, pressure, SDD and depth. Additionally, ion chamber volume averaging effect, \(k_{s}\), in equation (6) was shown to be the same for all chambers and therefore not applied. Despite the different SDD and thus a slightly different beam size at the position of the ion chamber than used during the measurements in the calorimeter phantom, differences in ion chamber stem corrections between the two chamber types were considered negligible. Corrections for electrometer calibration, \(k_{\text{elec}}\), were not applied since all ion chambers were measured with the same electrometer, at the same range and with the same collection potential (−250 V) applied. All ion chambers measurements at either 0 T and 1.5 T were performed on the same day.

Due to the nature of this experimental set-up measured ratios of ion chamber readings at either 0 T or 1.5 T were potentially more reliable than those in the calorimeter phantom. Therefore, erroneous results of a single chamber measurement in the calorimeter dataset could be detected as an outlier using this method. Note that direct transfer of the calorimetric \(D_{w}\) was not possible because different monitor ion chambers were used in both the calorimeter and the cross-calibration set-up. Note that equation (7) could have been expressed as ratios of chamber readings. However, it was chosen to express the values in terms of calibration coefficients because \(k_{B}\) values are based on a ratio of calibration coefficients according to equation (4).

3. Results

3.1. Calorimeter \(D_{w}\) measurements
Calorimetric determination of \(D_{w}\) are shown in table 1 and figure 2. For each group of \(\sim 30\) runs the mean and the standard deviation (SD) was determined. The standard deviation of the mean, SDOM, was calculated for the groups based on the square root of \(N\). It was shown to be less than 0.1\% and independent of the magnetic field. Additionally, the mean of the respective six and three groups was determined and the related SD of the means was calculated, referred to as the ‘actual SD of the means’ or ‘actual SDOM’. The ‘actual SDOM’ was respectively 0.26\% and 0.08\% for the six groups of \(D_{w}\) measurements with magnetic field and three groups of \(D_{w}\) measurements without magnetic field. If no additional day-to-day variation would be present, the SDOM should be the same as the ‘actual SDOM’. This is the case for the measurements without magnetic field. However, with magnetic field, the ‘actual SDOM’ is larger than the SDOM, indicating an additional day-to-day variation in the \(D_{w}\) measurements. This effect was also found in a previous study (de Prez et al 2019), where the day-to-day variation was presumably caused by the transmission monitor set-up in the MRI-linac with magnetic field and amounted to 0.16\% for measurements over a period of 4 days (de Prez et al 2019). In the current study, the calorimeter measurements with magnetic field took place at the start and end of a 19 day period. The \(D_{w}\) measurements, performed over the first days at the beginning of the respective periods were shown to be closer together than the final \(D_{w}\) measurements. This indicates the presence of a long-term (>10 d) day-to-day variation, larger than 0.16\%, previously determined over a period of 4 days. To account for this in the current study, the measured ‘actual SDOM’ is applied as the Type A uncertainty contribution, i.e. determined by repeated measurement, to the \(D_{w}\) for determination of the ion chamber magnetic field correction factor, \(k_{B}\). No additional day-to-day variation on the ion chamber measurements was applied, because this was accounted for by the variation in calorimetric \(D_{w}\) measurements. The dose-rate at the calorimeter reference conditions before
and after ramp-down was approximately 9.4 cGy s$^{-1}$, which relates at a 275 Hz PRF to a water absorbed-dose-per-pulse of approximately 0.34 mGy pulse$^{-1}$.

3.2. Ion chamber measurements

The ion chamber correction factors from equation (5), except for $k_{d, x}$, $k_{p, T}$ and $k_{s, 0}$, are given in Table 2. For all Farmer type chambers applied in this study with the same nominal cavity length of 2.3 cm, the volume averaging correction, $k_v$, from equation (6) was 1.0021 with magnetic field and 1.0023 with magnetic field. These values were in agreement with a volume averaging correction of 1.0021 calculated with a generic equation for FFF beams given by Palmans et al (2017). Despite a slight difference in beam profile between the lateral $x$ and $y$
3.3. Uncertainties in ion chamber \(k_Q\) and \(k_B\) factors

The uncertainty budget for \(D_u\) measurements with and without magnetic field was presented earlier (de Prez et al 2016a). It was shown that measurement of \(D_u\) with a water calorimeter and its related uncertainties are independent of the magnetic field, except for the larger Type A uncertainty in the repeated \(D_u/MU\) measurements, caused by the monitor set-up in the magnetic field. Therefore, the Type A uncertainty of 0.20% for repeated \(\Delta R/R\) measurements in table 3 of de Prez et al (2016a), was replaced by the Type A uncertainties of the current study, respectively 0.26% and 0.08%. Furthermore, the uncertainty in reference SDD \(k_{SDD}\) was adjusted from 0.02% to 0.05% caused by the alignment of the calorimeter in the MRI-linac bore. For the current study, this led to relative standard uncertainties in \(D_u\) for measurements at 1.5 T and at 0 T of respectively 0.53% and 0.38% (\(k = 1\)). The uncertainty in \(k_B\) and \(k_Q\) in this study was established in the same way as described earlier, taking correlation between the dose measurements in the denominator and nominator of equation (3) into account (de Prez et al 2016a, 2018b). The calorimetric contributions to the uncertainties in \(k_B\) and \(k_Q\) are shown in the first row of table 3. The ‘actual SDOM’ of calorimeter measurements, shown in table 1, is applied as the Type A uncertainty on determination of \(D_u\). The uncertainty for the ion chamber beam quality corrections at 0 T, \(k_{Q,B}\), is determined as the quadratic sum of the contributions reported in table 3 under \(^{60}\text{Co}\) and Q. The uncertainty for the ion chamber magnetic field corrections at 1.5 T, \(k_Q\), is determined as the quadratic sum reported in the table under Q and B at 1.5 T. The differences in uncertainty contributions to the SDD in \(^{60}\text{Co}\) and in the MRI-linac were accounted for in \(k_B\) because of the measurement in different facilities and therefore correlations do not apply. This means that 0.02% and 0.05% is accounted for in \(k_Q\) while only 0.05% is accounted for in \(k_B\). No distinction is made between the uncertainties in \(k_B\) factors for chambers placed in either antiparallel or perpendicular orientation to magnetic field. The uncertainty in \(k_{Q,B}\) is determined in a similar way to be 0.39%, but not shown in table 3. No uncertainty contribution was applied for the response change as a result of chamber misalignment with respect to its angle, which was expected to be smaller than 0.05% based on a potential misalignment smaller than 0.5° (Smit et al 2013).

3.4. Ion chamber consistency checks

Table 4 shows the ion chamber calibration coefficients, \(N_{D_u}\), of the six ion chambers based on direct calibration with the water calorimeter. Corresponding measurements without magnetic field were combined because no significant differences were seen between the chamber orientations. The table also shows the results of the additional cross-calibration, performed after removal of the calorimeter equipment from the MRI-linac bore. These results are expressed as relative deviations compared to the direct calibration coefficients, \(\Delta N_{D_u,0}\), where each chamber was cross-calibrated against the other five ion chambers. Per chamber type, field strength and chamber orientation, the standard deviation (SD) of the respective \(\Delta N_{D_u,0}\) for the three corresponding coefficients is reported. Table 4 shows that for individual chambers, deviations are mostly smaller than 0.10% and for some chambers about 0.25%. However, for chamber PTW 30013 with serial number 008474, deviations with magnetic field antiparallel and perpendicular are respectively +0.50% and −0.44% which influences respectively the \(k_{B||}\) and \(k_{B\perp}\) by the same amount. For the measurements without magnetic field,

**Table 3.** Uncertainty budget for \(k_Q\) and \(k_B\) factors in this study. All uncertainties are of Type B, except for the repeated chamber measurements, \(M/MU\).

| Source of uncertainty               | Measurement:                  | \(k_Q\) \(^{60}\text{Co}: 0\text{T}\) | \(Q: 0\text{T}\) | \(Q: 0\text{T}\) | \(Q: 1.5\text{T}\) |
|-------------------------------------|--------------------------------|---------------------------------------|----------------|----------------|------------------|
| \(D_u/MU\), contribution to \(k_B\) and \(k_Q\) measurements                  | 0.20                           | 0.08                                  | 0.08           | 0.26           |
| Charge measurement per monitor unit (M/MU), Type A                             | 0.10                           |                                       | 0.10           |                |
| Corrections for saturation and polarity, \(k_s\) and \(k_{pol}\)               | 0.07                           |                                       | 0.07           |                |
| Correction for \(p, T, k_{c,T}\) and relative humidity                        | 0.15                           |                                       | 0.15           |                |
| Correction to reference SDD, \(k_{SDD}\)                                     | 0.02                           | 0.05                                  |                |                |
| Correction to reference depth in water, \(k_d\)                               | 0.04                           |                                       | 0.04           |                |
| Relative combined standard uncertainty \((k = 1)\)                            | 0.30                           |                                       | 0.34           |                |
The SDs of the differences are smaller than 0.10%. SDs for measurements with magnetic field are larger and range between 0.10% and 0.35%. Similar to the $D_{w/MU}$ measurements, SDs without magnetic field are smaller than with magnetic field. Pojtinger et al (2018) also observed larger day-to-day variation for their experiments with Farmer type ion chambers in a magnetic field for which the reason remained unresolved. However, based on the SDs given in table 4, it can be concluded that the individual ion chamber measurements show an adequate consistency as a basis for the generic $k_Q$ and $k_B$ data per chamber type, reported in table 5. Therefore, no direct calorimeter calibrations were rejected.

### 3.5. Ion chamber $k_Q$ and $k_B$ factors

Ion chamber $k_Q$ and $k_B$ values and their uncertainties are given in table 5. Ion chamber calibrations were based on the calorimetric $D_w$ measurements with the high-purity cell in antiparallel as well as perpendicular direction to the bore, both with and without magnetic field. The $^{60}$Co measurements at 0 T, before and after the measurements at the MRI-linac, were performed in a similar way as described earlier (de Prez et al 2016a). $k_B$ values were entirely based on the measurements done at 1.5 T, before magnet ramp-down and at 0 T, just after magnet ramp-down. Therefore, the reported $k_B$ is independent on the $^{60}$Co measurements. Variation of $D_w$ in $^{60}$Co, used for determination of $k_Q$, before and afterwards was smaller than 0.05%, confirming a chemically stable HPC and thermistor calibration during the measurements in the MRI-linac. The uncertainties on the generic $k_Q$ and $k_B$ values are established by adding the uncertainties reported in table 3 to the relative standard deviation, SD, reported in table 5. $k_{Q,B}$ factor can be obtained by multiplication of $k_Q$ and $k_B$ according to equation (4).

### Table 4

Direct calibration coefficients for the six ion chambers measured without magnetic field, $N_{D_w,Q}$, and with magnetic field in antiparallel and perpendicular orientation, respectively $N_{D_w,Q,∥}$ and $N_{D_w,Q,⊥}$. The cross-calibration coefficients were based on the same calorimeter $D_w$ values as the direct calibration coefficients.

| Chamber       | sn       | $N_{D_w,Q} \ (\text{mGy pC}^{-1})$ | $\Delta N_{D_w,Q} \%$ | $N_{D_w,Q,∥} \ (\text{mGy pC}^{-1})$ | $\Delta N_{D_w,Q,∥} \%$ | $N_{D_w,Q,⊥} \ (\text{mGy pC}^{-1})$ | $\Delta N_{D_w,Q,⊥} \%$ |
|---------------|----------|-----------------------------------|-----------------------|-----------------------------------|-----------------------|-----------------------------------|-----------------------|
| PTW 30013     | 007120   | 52.53                             | $+0.07$               | 52.04                             | $-0.15$               | 50.65                             | $+0.24$               |
|               | 008377   | 52.74                             | $-0.03$               | 51.81                             | $-0.01$               | 50.66                             | $+0.04$               |
|               | 008474   | 52.52                             | $+0.02$               | 51.54                             | $+0.50$               | 50.68                             | $-0.44$               |
| SD            |          |                                   |                       |                                   |                       |                                   |                       |
| IBA FC65-G    | 3129     | 47.50                             | $-0.08$               | 47.20                             | $+0.02$               | 45.29                             | $+0.16$               |
|               | 3212     | 47.52                             | $+0.03$               | 47.38                             | $-0.25$               | 45.52                             | $-0.04$               |
|               | 3213     | 47.40                             | $+0.05$               | 47.19                             | $-0.11$               | 45.29                             | $+0.06$               |
| SD            |          |                                   |                       |                                   |                       |                                   |                       |

### Table 5

This study’s ion chamber $k_Q$ and $k_B$ factors with magnetic field in antiparallel ($\parallel \ 180^\circ$) orientation and perpendicular ($\perp \ -90^\circ$), orientation. $k_{Q,B}$ factors can be obtained by multiplication of $k_Q$ and $k_B$.

| Chamber       | sn       | $k_Q$  | $k_B$  | $k_B$  |
|---------------|----------|--------|--------|--------|
|               |          | $||$   | $\perp$ | $\perp$ |
| PTW 30013     | 007120   | 0.985  | 0.991  | 0.964  |
|               | 008377   | 0.988  | 0.982  | 0.961  |
|               | 008474   | 0.982  | 0.982  | 0.965  |
| SD /%         |          | 0.3    | 0.5    | 0.2    |
| generic       |          | 0.985(5) | 0.985(6) | 0.963(4) |
| IBA FC65-G    | 3129     | 0.990  | 0.994  | 0.953  |
|               | 3212     | 0.993  | 0.997  | 0.958  |
|               | 3213     | 0.987  | 0.996  | 0.956  |
| SD /%         |          | 0.3    | 0.2    | 0.2    |
| generic       |          | 0.990(5) | 0.995(4) | 0.956(4) |
Table 6. This study’s ion chamber $k_Q$ and $k_B$ factors compared to available literature values. Note that the Monte Carlo studies included the ion chamber sensitive volume, indicated with SV (Butler et al 2015, Malkov and Rogers 2017, Spindeldreier et al 2017) in the calculation of $k_B$, which is intrinsically incorporated in the measured $k_B$ values.

| Chamber       | Study                        | Method               | $k_Q$       | $k_{B\parallel}$ | $k_{B\perp}$  |
|---------------|------------------------------|----------------------|-------------|------------------|---------------|
| PTW 30013     | van Asselen et al (2018)     | Measured             | —           | 0.992(2)         | 0.963(2)      |
|               | Malkov and Rogers (2018)     | Monte Carlo—SV       | 0.984(1)    | 0.988(1)         | —             |
|               | Poettinger et al (2018)      | Monte Carlo          | —           | 0.996(2)         | —*            |
|               | Spindeldreier et al (2017)   | Monte Carlo—SV       | —           | 0.993(3)         | 0.954(3)      |
|               | O’Brien et al (2016)         | Monte Carlo          | —           | 0.994(1)         | 0.976(1)      |
| Mean (SD)     |                              |                      | —           | 0.993(3)         | 0.964(11)     |
| Difference    | from this study              |                      | −0.1(5)%    | +0.8(7)%         | +0.1(12)%     |
| IBA FC65-G    | van Asselen et al (2018)     | Measured             | —           | 0.997(3)         | 0.952(2)      |
|               | Malkov and Rogers (2018)     | Monte Carlo—SV       | 0.988(1)    | 0.992(1)         | —*            |
| Mean (SD)     |                              |                      | —           | 0.995(4)         | 0.952(2)      |
| Difference    | from this study              |                      | −0.2(5)%    | −0.1(6)%         | −0.4(5)%      |

* These studies reported values in perpendicular direction to the magnetic field, however with the chamber in opposite orientation to the other studies reported in the table. It was shown in the reported studies that ‘perpendicular’ and ‘anti-perpendicular’ value for $k_B$ could give different results. Therefore, these values are not reported here.

4. Discussion

4.1. Measurement of $k_Q$ and $k_B$

$k_Q$ and $k_B$ values for ion chambers, reported in table 5, were measured with uncertainties of respectively 0.30% and 0.34%, given in table 3. The major contribution to these uncertainties were of Type A, obtained from repeated calorimeter measurements, $D_{w/MU}$, in $^{60}$Co and in the MRI-linac with magnetic field. The Type A uncertainty in the calorimeter measurements with magnetic fields (0.26%) was higher than that without magnetic field (0.08%). This was presumably caused by day-to-day variations in normalization due to the transmission monitor set-up inside the magnetic field of the MRI-linac (de Prez et al 2019). To reduce this uncertainty contribution for future measurement the independent monitor set-up needs to be improved. Other uncertainty contributions in the MRI-linac determination of $k_Q$, the same as in conventional linac beams, except for the uncertainty in correction to reference SDD, $k_{SDD}$. This was adjusted from 0.02% to 0.05% due to the alignment of the calorimeter in the MRI-linac bore. Ion chamber corrections for volume averaging, $k_v$, were smaller than previously measured in conventional FFF beams and larger than those in beams with flattening filter (de Prez et al 2018b). This was mainly caused by beam flattening due to an increased SDD in the MRI-linac (139.3 cm) compared to the SDD in conventional linacs as given by Palmans et al (2017). Corrections for recombination and polarity, presented in table 2, confirm that, for the applied ion chambers, the polarity correction is both independent on beam modality and magnetic field within the reported uncertainty. $k_v$ in a continuous beam of $^{60}$Co is very small (<0.1%) as expected and mainly caused by initial recombination (Boutillon 1998). A consistency check by independent cross-calibration of each ion chamber against the other five, showed adequate consistency as a basis for the generic $k_Q$ and $k_B$ data per chamber type as reported in table 5. However, also here the measurements with magnetic field showed a larger SD than without magnetic field.

4.2. Comparison of $k_Q$ and $k_B$ with current literature

$k_Q$ factors were determined independent of chamber orientation. $k_B$ factors were determined in two orientations, antiparallel ($\parallel -90^\circ$) and perpendicular ($\perp 180^\circ$) to the transverse magnetic field. Table 6 gives currently reported literature values. All currently available values were reported with their Type A uncertainties only. The values summarized in table 6 represent the unweighted means, which assumes that the overall uncertainties of the reported values (i.e. Type A plus Type B uncertainties) are very close to each other. Differences between beam profiles with and without magnetic field are not considered to affect $k_B$ factors. The study by Malkov and Rogers (2018) is the only study that also reports Monte Carlo calculated $k_Q$ values for the same ion chambers and MRI-linac as applied in the current study at 0 T. The other studies assume that $k_Q$ values for the MRI-linac can be taken from existing CoPs, which is not trivial because the MRI-linac FFF beam is affected by the MRI-cryostat (Woodings et al 2018). Differences in ion chamber volume averaging, $k_v$, must be considered when comparing $k_Q$ values. In the current study, $k_Q$ values in table 6 did not include chamber volume averaging effect. Table 6 gives the differences between the mean of the earlier reported values in literature and the values obtained in the current study. Differences for $k_B$ range from −0.4% to +0.8%. Differences in $k_Q$ based only on one study (Malkov and Rogers 2018) are smaller than 0.2%. All results are well within the expanded uncertainties ($k = 2$).
of their differences. The largest difference from literature of 0.8% is observed for the $k_{q\perp}$ of the PTW 30013 type. However, this value is consistent with the performed cross-calibration against the other five ion chambers and there is no reason to reject this value. In general, it can be concluded that the values presented in table 5 are currently the best estimates provided with a comprehensive uncertainty budget for $k_Q$ and $k_B$, both $\parallel 180^\circ$ and $\perp -90^\circ$, in the Elekta Unity 7 MV MRI-linac.

The only studies basing their results on measurements are the current study and the study by van Asselen et al (2018). It is known that the chamber sensitive volume described by Butler et al (2015) plays a significant role in $k_B$ and subsequently the orientation of the chamber in the magnetic field (Malkov and Rogers 2017, Spindeldreier et al 2017). This must be accounted for correctly when calculating $k_B$ by Monte Carlo methods. The reported Monte Carlo studies only accounted for this in a quantitative way, i.e. based on matching Monte Carlo calculations with experiments. However, since the exact ion chamber dead-volume is currently unknown and is dependent of chamber guard construction, thus chamber type, this introduces an increased Type B uncertainty in the calculations. This is not covered by the reported uncertainties of the current Monte Carlo studies.

5. Conclusion

This study reports, for the first time, measured $k_Q$ factors at 0 T and $k_B$ factors at 1.5 T in a 7 MV photon beam of a pre-clinical Elekta Unity MRI-linac. The measurements were based on direct calibrations, traceable to the Dutch primary standard for absorbed dose to water, operated on-site in the bore of the MRgXT device. Despite variations in measurements with magnetic field, the values presented are currently the best estimated provided with a comprehensive uncertainty budget for generic $k_Q$ and $k_B$, both antiparallel ($\parallel 180^\circ$) and perpendicular ($\perp -90^\circ$), for PTW 30013 and IBA FC65-G chambers in the Elekta Unity MRI-linac. Partly because of the relatively large SD of the available literature values (up to 1%), agreement was shown with the values presented in the current study.

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