Technical Note

Influence of beam quality on reference dosimetry correction factors in magnetic resonance guided radiation therapy

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\begin{abstract}
Correction factors for reference dosimetry in magnetic resonance (MR) imaging-guided radiation therapy ($k_{B\rightarrow M Q}$) are often determined in setups that combine a conventional 6 MV linac with an electromagnet. This study investigated whether results based on these measurements were applicable for a 7 MV MR-linac using Monte Carlo simulations. For a Farmer-type ionization chamber, $k_{B\rightarrow M Q}$ was assessed for different tissue-phantom ratios ($TPR_{43} = 0.0029(43)$ between $TPR_{23} = 0.6790(23)$ (6 MV linac) and $TPR_{23} = 0.7028(14)$ (7 MV MR-linac) at 1.5T. The agreement was best in an orientation in which the secondary electrons were deflected to the stem of the ionization chamber.
\end{abstract}

1. Introduction

Magnetic resonance-guided radiation therapy (MRgRT) is a new modality in image guided radiotherapy where the target position is determined by magnetic resonance imaging (MRI) in real-time before and during the irradiation. Because of the good MRI soft tissue contrast, this leads to an improved patient positioning and therefore also potentially to improved tumor conformity \cite{1-4}.

On the other hand, the MRI of the MR-linac introduces challenges for absolute dosimetry. This is because it is impossible to turn off the magnetic field in clinical practice, due to the high cost and time demands. However, ionization chambers, which are typically used for this kind of measurements are influenced by magnetic fields \cite{5}. To compensate for this effect, an additional magnetic field correction factor must be applied to the reading of ionization chambers. Recently, several authors have published simulated as well as experimentally determined magnetic field correction factors for Farmer-type ionization chambers \cite{5-14}. The magnetic field correction factor $k_{B\rightarrow Q}$ can be defined as \cite{13}:

$$ k_{B\rightarrow Q} = k_{B\rightarrow MQ} \cdot c_{B} $$

(1)

Here, $k_{B\rightarrow MQ}$ is the ratio between the reading of the ionization chamber in the presence of a magnetic field and the reading without a magnetic field. For the calculation of $k_{B\rightarrow MQ}$ the readings must be corrected for other influences, such as air pressure and temperature. The dose conversion factor $c_{B}$ is calculated as the ratio of the absorbed dose-to-water at the point of measurement in the absence of a magnetic field to the absorbed dose-to-water at the point of measurement in the presence of a magnetic field.

One approach to determine $k_{B\rightarrow MQ}$ was proposed based on experiments that were carried out in setups that combine a conventional 6 MV linac with an electromagnet \cite{5,7,14}. In such experimental setups, it is not possible to determine $k_{B\rightarrow Q}$ directly. To measure $c_{B}$ experimentally, a detector which is not influenced by the magnetic field would need to be used. On the other hand, the determination of $k_{B\rightarrow MQ}$ is possible in experimental setups that combine an electromagnet with a conventional linac \cite{7,13}. In this case, for the calculation of $k_{B\rightarrow Q}$, $k_{B\rightarrow MQ}$ must be multiplied with $c_{B}$ in an additional step. To do this, $c_{B}$ must be calculated by Monte Carlo simulations for the respective beam quality of the MR-linac, as done in \cite{13}. The spread in the results for magnetic field correction factors that were determined by different methods is approximately 1% \cite{15}.
As the beam quality of conventional linacs differs from the beam quality of the two clinically available MR-linacs, that is 6 MV flattening filter free (FFF) for the 0.35 T MR-linac [16] and 7 MV FFF for the 1.5 T MR-linac [17], the determination of the magnetic field correction factors that have been determined in a 6 MV setup were also valid for use also at 7 MV FFF MR-linacs.

The aim of this study was to investigate whether the magnetic field correction factors found for Farmer type ionization chambers [10] are different between a 6 MV in a conventional linac and 7 MV FFF in a 1.5 T MR-linac.

2. Materials & methods

2.1. Calculation of \( k_{B,M,Q} \)

EGSnrc, a Monte Carlo code system [18] was used to simulate the energy deposition in the sensitive volume of a Farmer-type ionization chamber that was positioned inside a water tank. This was undertaken for both beam qualities (6 MV and 7 MV FFF) and for different magnetic flux densities.

To do this, a model of a PTW 30013 (PTW, Freiburg, Germany) Farmer-type ionization chamber was created in EGSnrc using the egs_chamber user code [19]. The dead volume inside the sensitive volume of the ionization chamber was modelled by a finite element simulation of the electric field inside the ionization chamber, as described in detail in our previous work [7].

Accelerator head models of a 6 MV linac (Elekta Precise, Elekta AB, Stockholm, Sweden) and the 7 MV FFF MR-linac (Unity, Elekta AB, Stockholm, Sweden) were created for the EGSnrc user code BEAMnrc [20,21]. Both accelerator head models were compiled as a shared library, so they could be used as a source in egs_chamber.

The models of the Farmer type ionization chamber as well as of the 6 MV linac were already used in a previous investigation [7]. In this study, Monte Carlo simulated results based on these models were successfully benchmarked with experimental results [7]. The accelerator head model of the 7 MV FFF MR-linac was described and benchmarked against MR-linac measurements [21]. All simulation parameters were set in accordance with previous publications [6,7].

In the simulation geometry, the ionization chamber was placed at a 10cm depth inside a 30 × 30 × 20cm³ water cuboid. The ionization chamber was placed in an orientation, in which the ionization chamber axis was perpendicular to the magnetic field vector. The beam direction was set perpendicular to the magnetic field vector, as well as to the ionization chamber axis (Fig. 1).

The magnitude of the magnetic field correction factors \( B \) was determined in negative values, if the secondary electrons were deflected to the tip of the ionization chamber, and this was defined in positive values, if the secondary electrons were deflected to the stem of the ionization chamber.

Simulations were done for magnetic flux densities up to \( B = 1.5T \) in steps of 0.15T (Fig. 2).

The results were used to calculate \( k_{B,M,Q} \) in dependence of the magnetic flux density:

\[
 k_{B,M,Q} = \frac{E_{dep}}{E_{dep}^{\text{ref}}} \tag{2}
\]

Here, \( E_{dep} \) is the deposited energy scored in the sensitive volume of the ionization chamber for \( B = 0 \)T and \( E_{dep}^{\text{ref}} \) is the deposited energy scored for a specific magnetic flux density \( B \), for the same irradiation conditions.

2.2. Calculation of the tissue-phantom-ratio

The beam quality of the implemented accelerator head models was quantified by calculating the tissue-phantom ratio (TPR). To do this, the deposited energy was scored in a cylindrical volume that was placed in the middle of the water cuboid at a 10cm depth \( (E_{dep})^{\text{ref}} \). The thickness and radius of the cylinder were set to 0.2mm and 1mm, respectively. A second simulation was carried out, in which the size of the water phantom was symmetrically increased to \( 30 \times 30 \times 40\text{cm³} \). For this, the position of the cylinder was not changed, so that the water cylinder was placed at a depth of 20cm. Again, the deposited energy was scored in the cylindrical volume \( (E_{dep}^{\text{test}}) \).

For all simulations, the cylinder was placed at the isocentre of the corresponding accelerator. The distance between the source and the scoring volume was therefore set to 100cm for the 6 MV linac beam model and 143.5cm for the 7 MV FFF MR-linac beam model. The TPR at the depths of 20cm and 10cm \( (TPR_{20,10}) \) was calculated to quantify the beam quality for a field size of \( 10 \times 10\text{cm²} \) [22]:

\[
 TPR_{20,10} = \frac{E_{dep}^{\text{test}}}{E_{dep}^{\text{ref}}} \tag{3}
\]

For the simulation of \( TPR_{20,10} \), the magnetic flux density was set to \( B = 1.5T \).

The uncertainties given in this work were calculated by multiplying the standard deviation of the Monte Carlo results by a factor of 2.

Fig. 1. Schematic representation of the orientation of the magnetic field vector (\( \mathbf{B} \)), the radiation beam direction, the Lorentz force (\( \mathbf{F}_L \)) and the ionization chamber axis.
The maximum difference for the different beam qualities was found for $B = -1.35T$. For this magnetic flux density, the effect of the magnetic field was more prominent for the 6 MV beam quality and differed by 0.0055(44) from the 7 MV FFF beam quality. Also, for $B = -1.05T$, the results differed by 0.0052(44). For all other magnetic flux densities, the differences were within the uncertainty intervals, that never exceeded 0.0047. For $B = -1.5T$ and $B = 1.5T$ the results differed by 0.0020(43) and 0.0029(43). The calculation of $TPR_{20.10}\,\rightarrow\,Q_{\text{PTW 30013}}$ resulted in $TPR_{20.10} = 0.7028(14)$ for the 7 MV MR-linac and $TPR_{20.10} = 0.6790(23)$ for the 6 MV linac.

### 3. Results

In contrast, the results of this work do not agree with the Monte Carlo simulations in this work. The same applies the 7 MV FFF beam quality from 6 MV to 8 MV (conventional linac), compared to 6 MV (conventional linac). However, it can be speculated, that the effect of the change of beam quality on the secondary electron spectrum inside the ionization chamber is small, for a change of beam quality between 6 MV and 7 MV FFF.

These results can be compared to the experimental results of Gohil et al.\[[14]\]. The authors found that $k_{B,MQ}^{\leftrightarrow}$ differed by 0.51%, comparing the 6 MV beam quality to the 8 MV beam quality. Gohil et al.\[[14]\] did not report any beam quality specifier. Therefore, it cannot be concluded how close the 6 MV and 8 MV beam quality of the conventional linac used by Gohil et al.\[[14]\] is to the 6 MV beam quality that was used for the Monte Carlo simulations in this work. The same applies the 7 MV FFF beam quality of the 1.5 T MR-linac. However, it can be speculated, that the change in the photon spectrum is more dominant for a change of beam quality from 6 MV to 8 MV (conventional linac), compared to 6 MV (conventional linac) to 7 MV FFF (MR-linac). In this sense, the study of Gohil et al.\[[14]\] supports our conclusion, that the change of the beam quality between a conventional 6 MV linac and a 7 MV MR-linac does not influence $k_{B,MQ}^{\leftrightarrow}$ by more than approximately 0.5%.

For the 7 MV FFF beam quality, the simulated beam quality specifier $TPR_{20.10}$ is in excellent agreement with experimental results that can be found in the literature\[[12,23]\]. De Prez et al.\[[12]\] found $TPR_{20.10} = 0.701(2)$ and Snyder et al.\[[23]\] published a value of $TPR_{20.10} = 0.704$. In contrast, the results of this work do not agree with the Monte Carlo simulated values of other authors\[[9,10]\]. These authors published $TPR_{20.10} = 0.695$ and $TPR_{20.10} = 0.691(1)$, respectively.

The limited space between the pole shoes of an electromagnet might result in an additional problem as this limits the maximum field size and the size of the phantom. A recent publication showed that a reduction of the field size to $3 \times 10\,\text{cm}^2$ can influence the results for $k_{B,MQ}^{\leftrightarrow}$ by 0.4%\[[8]\].

In conclusion, this study revealed that the change of the beam quality between $TPR_{20.10} = 0.6790(23)$ (6 MV linac) and $TPR_{20.10} = 0.7028(14)$ (7 MV MR-linac) did not influence $k_{B,MQ}^{\leftrightarrow}$ more than 0.5%, for the PTW 30013 ionization chamber in perpendicular orientation.

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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