Quality correction factors for small-cavity ionization chambers in small MR-guided radiotherapy beams

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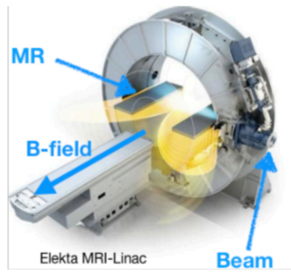
INTRODUCTION

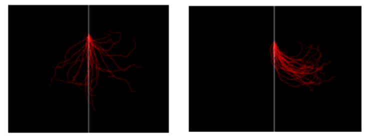
In magnetic resonance guided radiation therapy (MRgRT), radiation delivery can be more precise by focusing radiation dose on the tumour and sparing healthy tissue. Treatment planning systems require accurate dosimetry measurements. Regular use of small photon beam for complex MRgRT is anticipated. In small-field dosimetry, small-cavity chambers are recommended for reference dosimetry.



What is the effect of the magnetic field?

- Electrons are affected by an additional force (Lorentz force).
- Trajectories are modified depending on the strength of the magnetic field (B-field) and on the medium density.
- Secondary radiation field and detector signal are modified.

Electrons in water



0 T   1.5 T

What is the effect of the small fields?

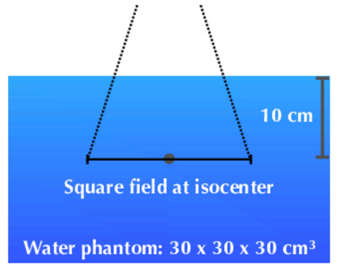
- Perturbation of the lateral charged particle equilibrium.
- Detector size is comparable to the radiation field size disturbing the field uniformity.
- Density and volume averaging perturbations increases [1-3].

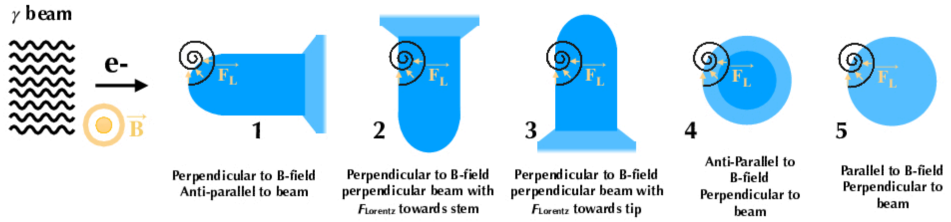
AIM

Determine the optimal chamber orientation for dosimetry measurements in small-fields coupled to magnetic fields by evaluating perturbation and quality correction factors of small-cavity chambers.

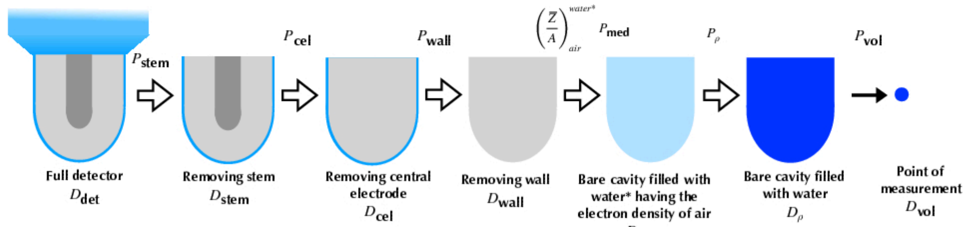
METHOD

- Monte Carlo calculations (EGSnrc) of small-cavity chamber dose response in a water phantom irradiated by an ELEKTA MR-Linac Unity photon beam at 0 T and 1.5 T.
- Chamber models: PTW31010, PTW31021 and PTW31022, previously validated [4], the sensitive volume is determined by simulating the electric field inside the chamber.
- Five squared fields of size widths: 1 cm, 2 cm, 3 cm, 5 cm and 10 cm.
- Five chamber orientations with respect to photon beam and B-field direction:





Perturbation factors are determined by gradually modifying the geometry and calculating the ratio of doses in modified geometries [5-6], as follows:

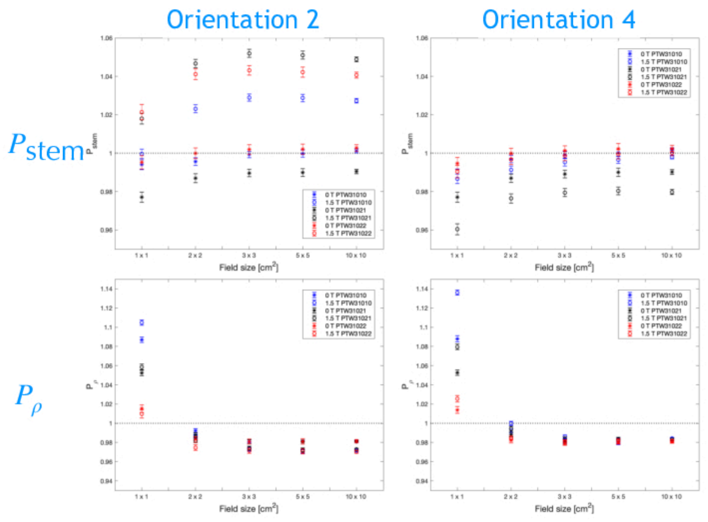


The **quality correction factor,** accounting for B-field effects, is the ratio of the product of perturbation factors with and without B-field:

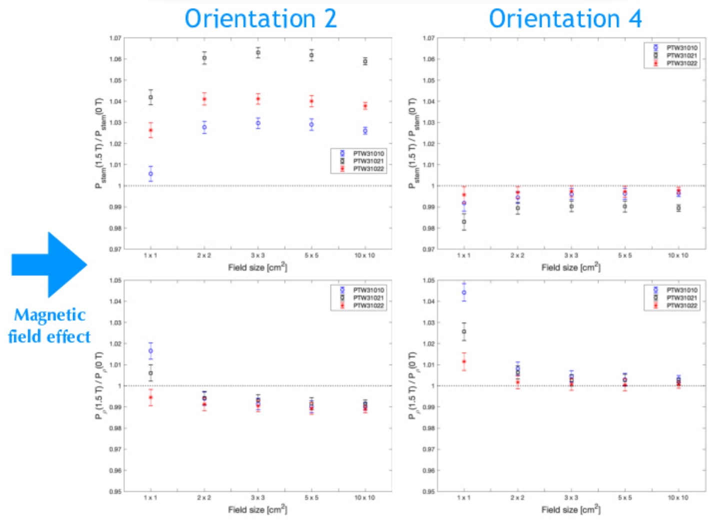
$$k_{Q_B,Q_O}^{f_B,f} = \frac{P(Q_B)}{P(Q_0)} = \frac{P_{\text{stem}}P_{\text{cel}}P_{\text{wall}}P_{\text{med}}P_{\rho}P_{\text{vol}}(Q_B)}{P_{\text{stem}}P_{\text{cel}}P_{\text{wall}}P_{\text{med}}P_{\rho}P_{\text{vol}}(Q_0)}$$

RESULTS

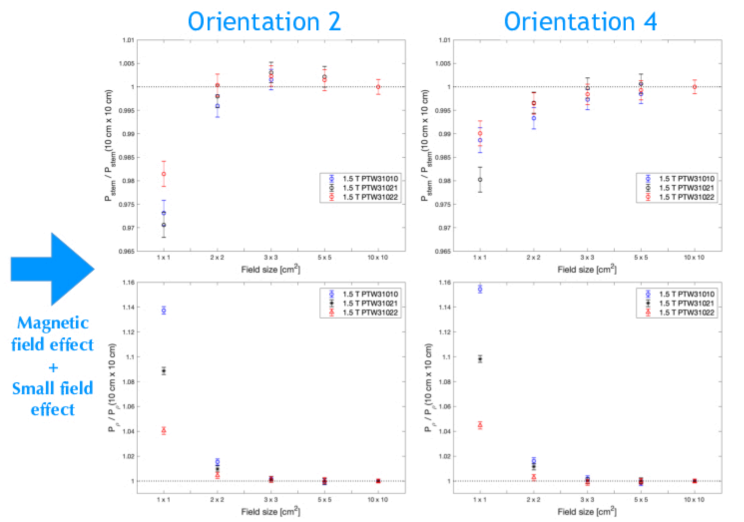
PERTURBATION FACTORS



Stem perturbation and density perturbation factors in orientation 2 and 4 of chambers PTW31010, PTW31021 and PTW31022 for 0 T and 1.5 T as a function of the field size.



Effect of the magnetic field on stem perturbation and density perturbation factors in orientation 2 and 4 of chambers PTW31010, PTW31021 and PTW31022 as a function of the field size.



Effect of the field size on stem perturbation and density perturbation factors in orientation 2 and 4 of chambers PTW31010, PTW31021 and PTW31022 as a function of the field size.

Perturbation factors

For all orientations, at 0 T and 1.5 T, perturbations are mostly constant for fields ≥ 2 cm x 2 cm.

- P_{stem} is amplified in orientations 1 and 2 up to 5.21%.
- P_{cel} is as large as to 2% for fields ≥ 2 cm x 2 cm and up to 4.1% for the field 1 cm x 1 cm.
- P_{wall} is the smallest of the extracameral perturbation factors, it is less than 1% for fields ≥ 2 cm x 2 cm and less than 2% for the field 1 cm x 1 cm.
- The atomic properties perturbation is constant in all cases: $P_{\text{med}} = 1.0186 \pm 0.0003$.
- P_{ρ} varies with orientation, B-field, field size and chamber model. For fields ≥ 2 cm x 2 cm, P_{ρ} is mostly constant. For 1 cm x 1 cm, P_{ρ} increases abruptly up to 1.14, the increment differs in every chamber model and orientation. P_{ρ} is one of the dominating factors over the other perturbation factors.
- P_{vol} remains mostly constant for each chamber, the maximal perturbation is up to 4% for fields ≥ 2 cm x 2 cm. For the field 1 cm x 1 cm, P_{vol} varies with orientation and chamber, the largest variation, 4%, occurs for PTW31010 in orientation 2.

Effect of the magnetic field on the perturbation factors

The effect of the B-field is different on every perturbation factors and it varies according to chamber orientation.

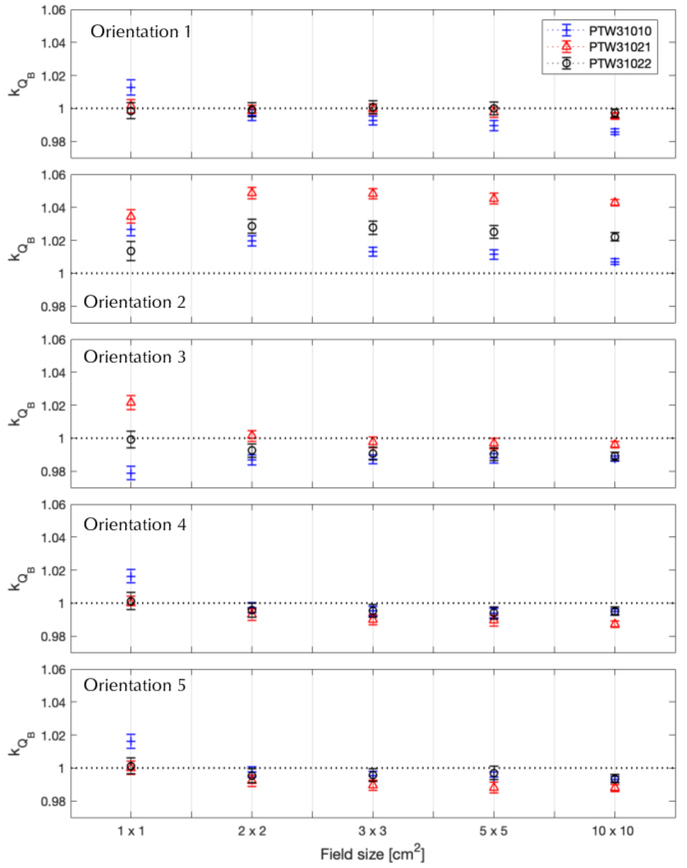
- For P_{stem}, the maximal B-field effect is approximately 2% in orientations 3-5, 4.2% in orientation 1 and 6.3% for orientation 2, this is due to the Lorentz force pointing towards the stem.
- For P_{cel}, in orientation 1, the B-field effect is constant over field size for each chamber, the maximal effect is around 1.0%. For orientations 2-5, the B-field effect is up to 1% for fields ≥ 2 cm x 2 cm and 2% for the field 1 cm x 1 cm.
- The B-field effect on P_{ρ} is highlighted in orientation 1, it is between 2.5-5% for all field sizes. For orientations 2-5, for the 1 cm x 1 cm field, the perturbation due to the B-field is accentuated and P_{ρ} increases as much as 5%.
- There is no significant effect of the B-field on P_{wall}, P_{med} nor on P_{vol}.

Effect of the field size on the perturbation factors

- With and without magnetic fields, the largest impact of the field size occurs on P_{ρ}. For the 1 cm x 1 cm field, the maximal effect of the field size is 15.4% while for fields ≥ 2 cm x 2 cm, the maximal effect is 1.8%.
- The effect of field size on P_{vol} is constant in fields ≥ 2 cm x 2 cm. For the 1 cm x 1 cm field, the effect increases as much as 6%, the increment depends on chamber orientation and increases with larger sensitive volume.

QUALITY CORRECTION FACTORS

- In orientations 4 and 5, chamber parallel to B-field, the k_{Q_B} factors are around 1% for all the studied cases
- In orientation 1, in most cases, k_{Q_B} is around 1% even if the chamber is perpendicular to the magnetic field. However the clinical setup is more challenging and might not be feasible.
- In orientations 2 and 3, chamber perpendicular to B-field, k_{Q_B} factors are larger. Specially in orientation 2 where the Lorentz force is pointing towards the stem on average.



Quality correction factors in orientation 1-5 of chambers PTW31010, PTW31021 and PTW31022 as a function of the field size.

CONCLUSIONS

- **Orientations where the chamber axis is aligned with the magnetic field yield k_{Q_B} factor closer to unity within 1%.**
- **The orientation where electrons are deflected towards the stem should be avoided.**
- **We recommend to perform measurements with the chamber orientation parallel to the magnetic field.**
- **The pinpoint 3D chamber PTW31022, which is the smallest, presents the smallest perturbation factors and thus a k_{Q_B} close to unity for all field sizes.**
- **kQB factors close to unity can be obtained for commercial chambers in small MRgRT beams.**

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