FINAL PUBLISHABLE REPORT

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Coordinator: Jacco de Pooter, VSL Tel: +31 6 11 83 53 78 E-mail: jdpooter@vsl.nl Project website address: https://mrgrtmetrology.com/		
Chief Stakeholder Organisation: IAEA	Chief Stakeholder Contact: Jamema Swamidas	
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1 Overview

There are 1.4M radiotherapy treatments in Europe annually, extensively using small radiation beams (x-rays or proton beams) to deliver optimized dose distributions to the cancer patient. MR guided RadioTherapy (MRgRT), the combined use of radiation beams to target the tumours and Magnetic Resonance Imaging (MRI) to provide image of soft tissue contrast, was recently introduced into clinics. This combined treatment has demonstrated the potential for delivering fewer adverse side-effects and more effective treatments, however full clinical utilisation of the treatment is hampered by the lack of standards for small field dosimetry. This project has delivered a methodology to extent the TRS-483 protocol for small field dosimetry towards application in MRgRT using x-rays (MRgXT). In addition, it has demonstrated traceable methods for MRgRT based on proton beams (MRgPT).

2 Need

MRgRT allows the patient anatomy to be imaged during the treatment and is therefore the next step in the ongoing development of radiotherapy to improve treatment efficacy. The number of clinical MR-guided X-ray Therapy (MRgXT) facilities (combining x-ray beams and MRI) has increased rapidly in the last few years which is expected to continue. Although not as clinically advanced, significant developments have also been made with MR-guided Proton Therapy (MRgPT) which combines proton beams and MRI.

For modern dose delivery techniques, the recent Code of Practice (CoP) TRS-483, enables medical physicists to perform traceable small field dosimetry. For MRgRT, small radiation fields are equally important and even though developments in MRgPT are lagging behind MRgXT, universities and industry, prior to the start of this projects, needed traceable methods for dosimetry to show the feasibility of dose delivery with MRgPT and to prepare for (pre)-clinical investigations.

In MRgRT, dosimetry needs to be performed in the presence of the magnetic field of the MRI scanner, which is known to affect both the (small) radiation field characteristics and the calibration of detectors. CoPs for small field dosimetry use an output correction factor to convert the detector calibration coefficient in a reference radiation field to small field based on the (small) radiation field characteristics. Consequently, existing CoPs for small field dosimetry are inadequate for application in MRgRT. Therefore, prior to the start of this project, medical physicists needed CoPs for traceable dosimetry for small fields in MRgRT.
Manufacturers have developed detectors for small field dosimetry in conventional radiotherapy. To assure the quality and the suitability of their products for application in small field dosimetry in MRgRT, they needed methods to assess detector characteristics in the presence of magnetic fields. The need for the work delivered in this project to elaborate standards for MRgXT and MRgPT harmonized with TRS-483 is also underlined by Standards Developing Organisations (SDOs) in their strategic documents; IAEA, IEC TC 62 and ISO/TC85/SC2.

3 Objectives

The project enabled traceable measurement of absorbed dose-to-water in small x-ray (photon) and proton beams (field size < 3 cm) in the presence of strong magnetic fields in support of future standards for small field dosimetry in MRgRT.

The specific objectives of the project were:

1. To determine a data set of correction factors and develop a measurement methodology for small fields in MRgXT extending the concept of IAEA/AAPM TRS-483 with a target uncertainty of 2.0 % (k = 1).
2. To investigate whether established traceable dose measurement methods for MRgXT and the concept of IAEA/AAPM TRS-483 can be adapted for scanned pencil-beam based MRgPT modalities.
3. To design and carry out Monte Carlo simulations of x-ray and proton beams in the presence of magnetic field to investigate radiation field characteristics, detector responses for on- and off-axis conditions and to determine detector properties and their suitability for small field dosimetry in MRgXT.
4. To design and carry out experiments (in laboratories and commercial MR-linacs) to provide dosimetrical measurement data on x-ray and proton beams in the presence of magnetic fields traceable to primary standards, to investigate radiation field characteristics and detector responses for

on- and off-axis conditions and to determine detector properties and their suitability for small field dosimetry in MRgXT and MRgPT.

5. To facilitate the take up of methods, technology, guidelines, Codes of Practice and measurement infrastructure developed in the project by the standards developing organizations (such as IAEA) and end-users, such as clinical stakeholders, and manufacturers of facilities and measurement equipment.

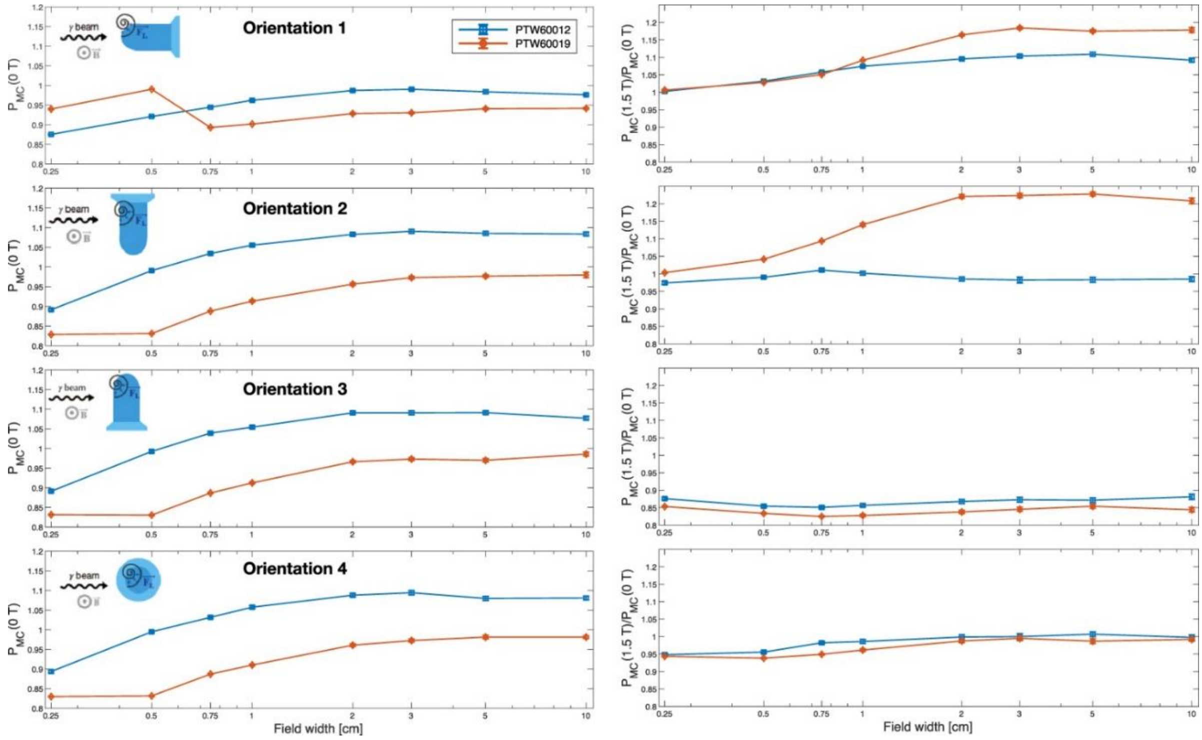
4 Results

4.1 Correction factors and methodology for small field dosimetry in MRgXT (Obj. 1)

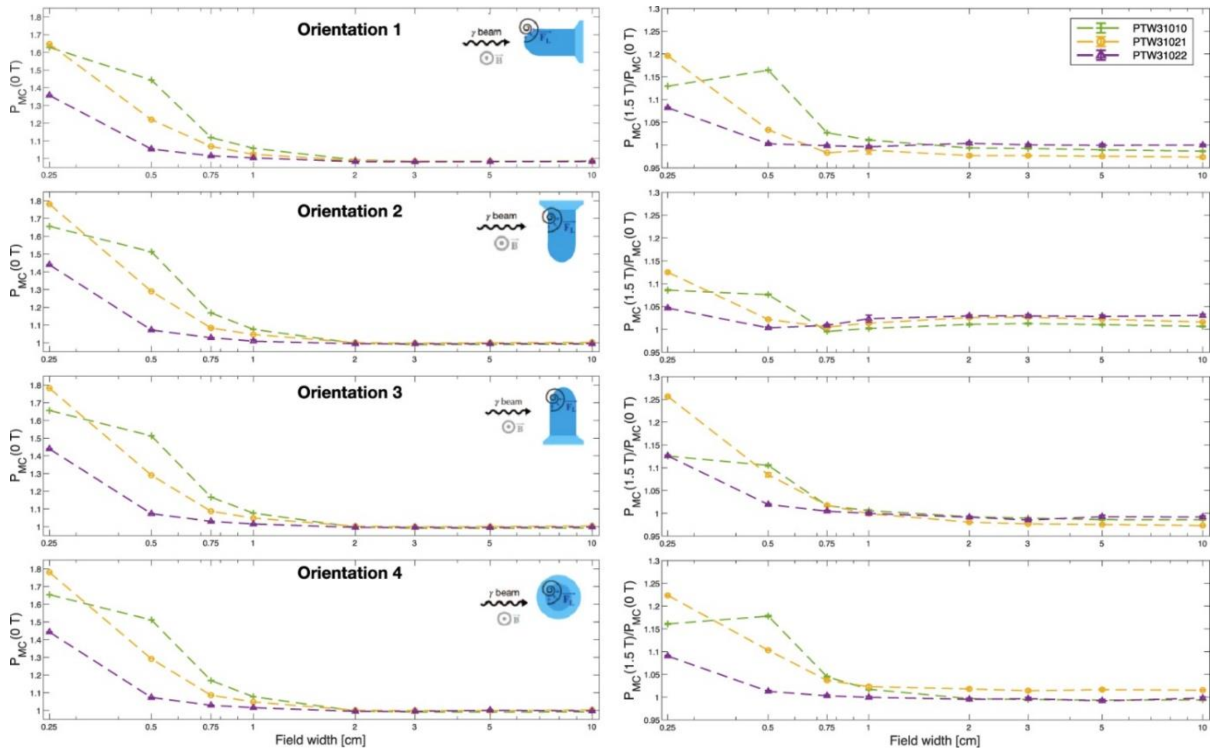
The development of Codes of Practice (CoPs) by SDOs strongly relies on the availability of data of correction factors. The data of correction factors published in the CoPs is usually specific for a certain detector type and is determined as the ratio of detector response under two different conditions (for example different beam qualities) and is based on either Monte Carlo radiation transport simulations, or measurements or a combination of both. The CoP TRS 483 for small field dosimetry provides so-called output correction factors which can be used to correct dosimetric measurements on small radiation fields in order to provide a more accurate value for the radiation dose.

In the predecessor project EMPIR 15HLT08 MRgRT, the accuracy of the Monte Carlo radiation transport simulations has been assessed by providing theoretical and experimental benchmarks. These investigations led to a set of input parameters to be provided to the investigated algorithms (PENELOPE and EGSnrc) to ensure accurate detector response simulations accounting for the presence of magnetic fields. This has resulted in adequate consistency between simulated and measured detector responses.

This project has built further on these investigations. By Monte Carlo radiation transport simulations, the first detector type specific correction factors for small square radiation fields in presence of magnetic fields have been determined by NPL in collaboration with the University of Montreal, see Figure 1, for three types of ionisation chambers and two types of solid state detectors. The product of the tabulated beam quality correction factor and the ratio between magnetic field correction factor in clinic and *msr* field, provides the output correction factor in the presence of magnetic field. These investigations were carried out by detailed investigations of the contribution of all subcomponents of the output correction factors. This provides more insight on the impact of the magnetic field on detector response. The results have been published in [2]. Other investigations using the same model demonstrate the negative impact of small air volumes in ionisation chamber for small field dosimetry in presence of magnetic fields. Based on this observation, one manufacturer has decided to change the chamber design in order to remove these small air cavities.



(a.)



(b.)

Figure 1 (a.) On the left side, overall perturbation correction factor of solid-state detectors for four orientations as function of the field sizes at 0 T. On the right side, the effect of the magnetic on PMC as a function of the field size. (b.) On the left side, the overall perturbation factor of ionization chambers, for four orientations as function of the field sizes at 0 T. On the right side, the effect of the magnetic on PMC as a function of the field size. (reproduced with permission from [2]).

In addition, a method has been developed by VSL to determine output correction factors in presence of magnetic fields using an existing dataset of output correction factors for conventional radiotherapy beams (i.e. without magnetic fields present) from public data. First, it was demonstrated by measurements of UMCU, that the data for 6 MV FFF conventional radiotherapy beams can be used as output correction factors in the Elekta Unity MR-linac when the magnetic field is switched off, see Figure 2. Second, the determined output correction factors for the magnetic field present have been validated against measurements in a clinical MR-linac facility (i.e. with the magnetic field present). These measurements demonstrated that the target uncertainty of 2.0 % could be achieved. These results provide traceable measurements on the beam axis of small square radiation fields in MRgXT facilities with a similar uncertainty as TRS-483.

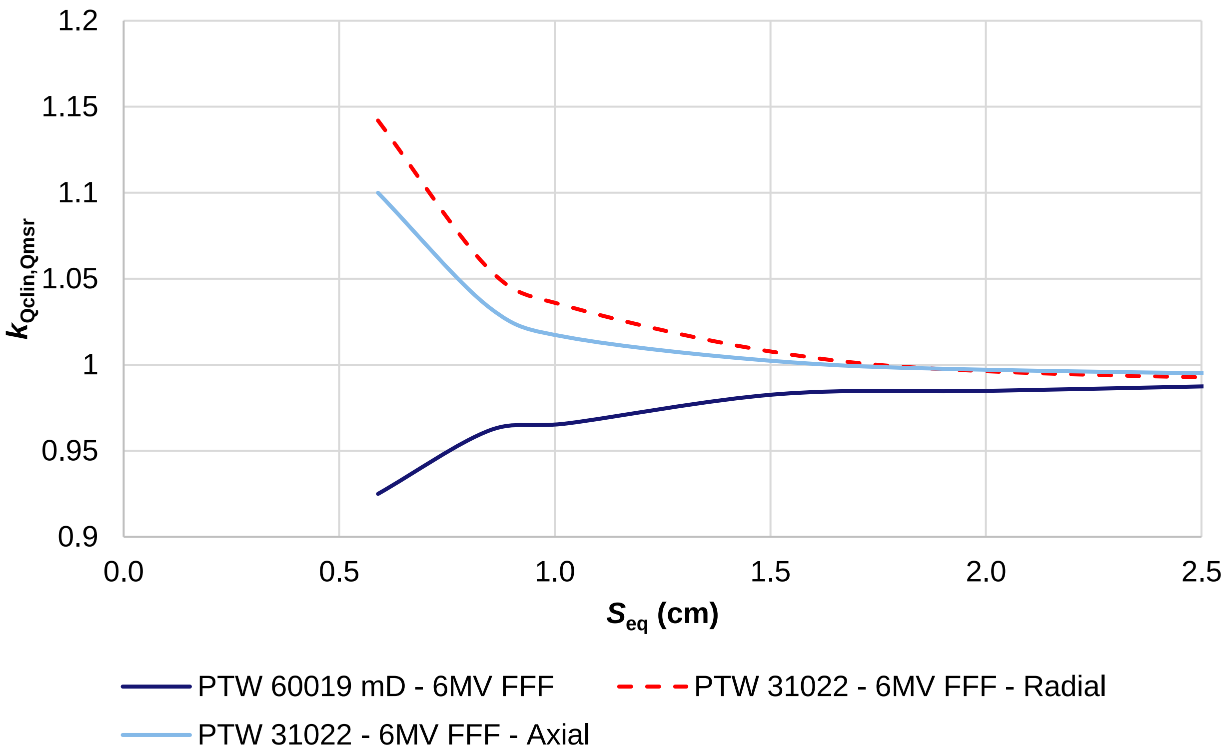


Figure 2 Output correction factors for a convention radiotherapy beam with an energy of 6 MeV and without flattening filter (FFF).

Measured (from PTB, NPL and DTU) and calculated output correction factors (from NPL and VSL) for both MR-linacs and experimental facilities were collected in an extensive data set. This includes data for other magnetic fields strengths (B_0 = 0.35 T), other field shapes (rectangular and off-axis) and using the maximum of the radiation field to position the detectors. In the review of this data set some discrepancies were identified in the set of output correction factors. Until now it was not possible to sort out the cause for these discrepancies. For the PTW 60019 diamond detector, output correction factors collected in this project were combined by PTB, using the same approach as TRS-483 (Figure 3). Subsets of data from the data set will be made publicly available once published in peer-reviewed papers. One subset has been published in https://doi.org/10.5281/zenodo.8413987.

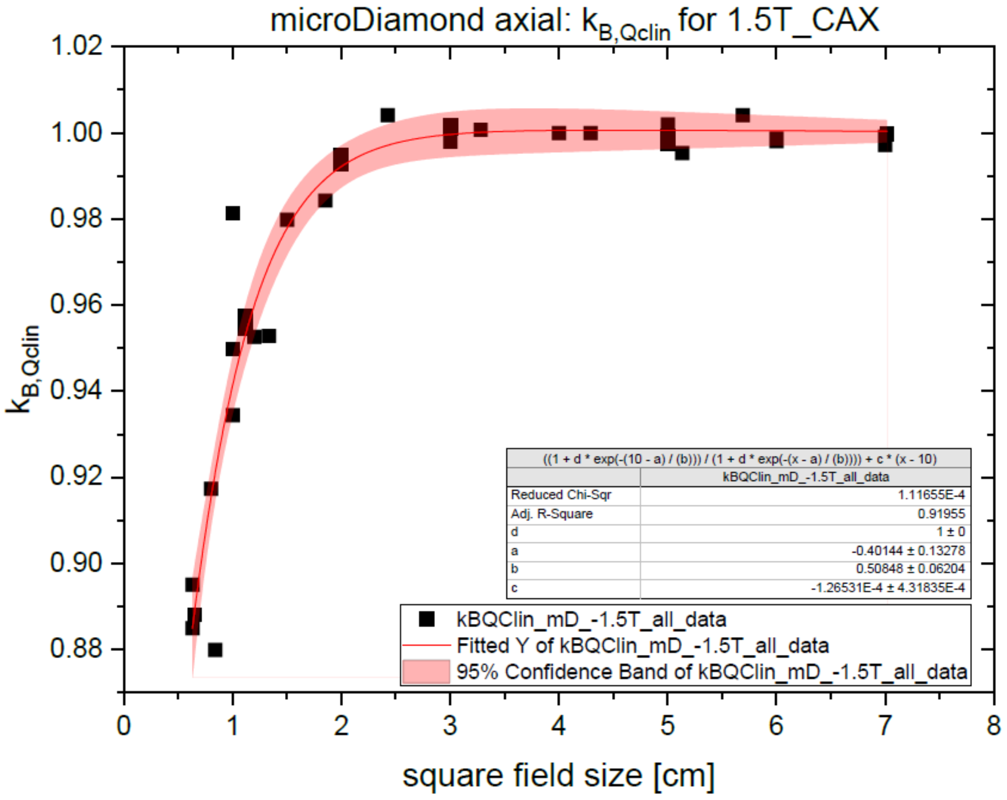


Figure 3 Output correction factors for the PTW 60019 detector using all data sets collected for this detector in the MRgRT-DOS project.

The consortium has drafted a formalism to extend TRS-483 for small field dosimetry. This formalism can be applied in conjunction with the above described data sets of correction factors for small square radiation fields in MR-linacs. In addition to the two above described methods, the project also prepared a method to determine the output correction factors by measurements. This method needs to vary the magnetic field strength. Since this is difficult to realize in MR-linacs, this method will mainly be used in combination with experimental facilities, such as those developed in this project by DTU, NPL and PTB (section 4.4).

The project partially achieved the objective and the key output of this project for this objective are:

1. A methodology has been developed to extend the TRS-483 formalism for small field dosimetry in MRgXT. This methodology includes three routes to determine output correction factors in presence of magnetic fields.
2. For two detectors it was demonstrated that existing TRS-483 output correction factors can be used in absence of the magnetic field in MR-linacs. This is the basis for two of the routes to determine output correction factors in presence of magnetic fields.
3. A large data set of output correction factors has been generated using the three routes and various facilities (both experimental and clinical) for various magnetic field strengths, detectors and field shapes.
4. For two detectors, It was demonstrated that the target uncertainty of 2.0 % can be met for square fields between 0.5 and 2.0 cm field sides.
5. For the PTW 60019 detector a first analysis on all collected output factors was conducted using the same approach as TRS-483.

4.2 Small field dosimetry for MRgPT (Obj. 2)

A key aspect in the development of CoPs is the reference field, which is a field with well-known characteristics which is used to perform the measurements and for which correction factors of secondary standards and detectors are available. IAEA/AAPM TRS-483 uses the concept of machine specific reference fields. In MRgPT the pencil proton beam travels through both the fringe and core magnetic field of the MRI scanner. Because protons are charged particles, these beams are deflected from their original trajectory when no magnetic field is present. Therefore, to extend this concept to MRgPT, it is essential to determine the impact of the 3D magnetic field on the deflection of the scanned proton beam.

The impact of the MR magnetic fields on the proton beam deflection and consequently on spot position was determined by radiochromic film measurements with and without magnetic field (Figure 4). After correction for an overall shift in spot position, it was demonstrated that also the spot pattern is deformed by the magnetic field (Figure 5). Apart from the expected energy dependent lateral shift in spot positions, and the observed deformation, an asymmetric vertical distortion in the spot shape was observed with maximum vertical displacement of the outer spots Figure 6.

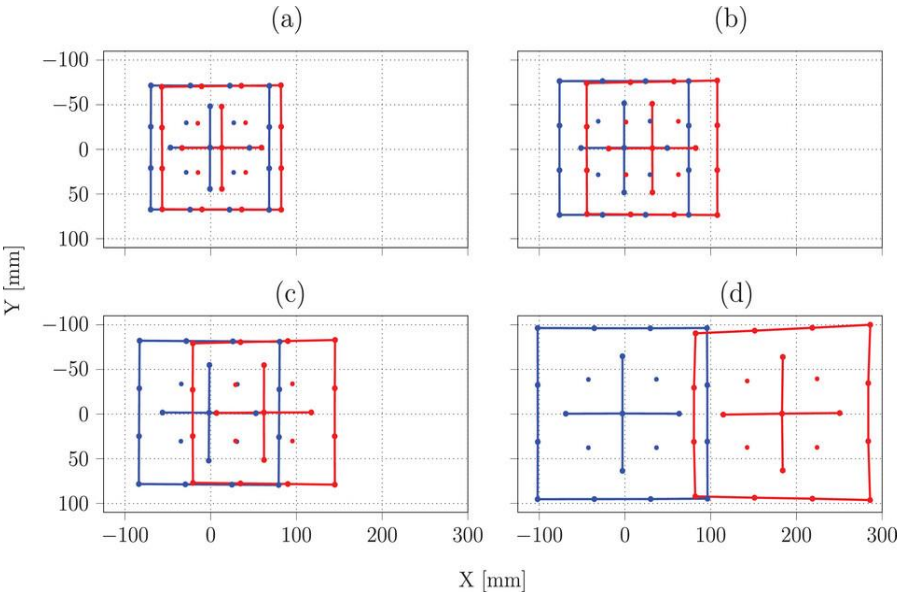


Figure 4 Beam's eye view of measured dose spot pattern deformation for the 15 × 15 cm2 dose spot patterns at locations A(a), B(b), C(c), and D(d) for 100-MeV pencil beams. The blue and red lines represent the field edges of the dose spot patterns without and with magnetic field, respectively. The dose spot positions are indicated by blue and red dots (reproduced with permission from [9]).

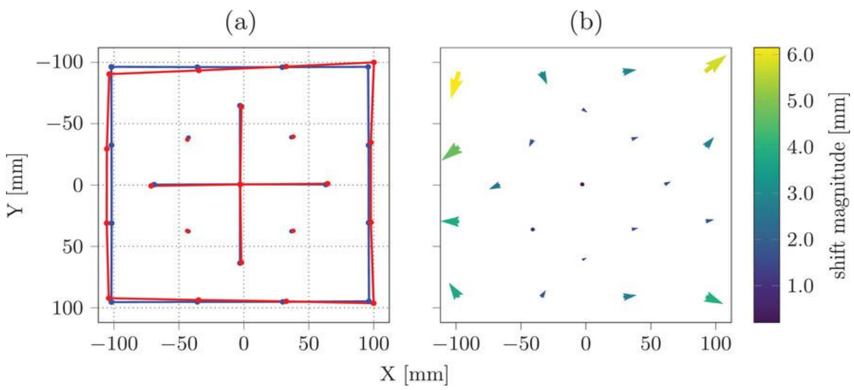


Figure 5 (a) Proton dose spot pattern deformation for 15 × 15 cm2 dose spot pattern at location D for 100-MeV pencil beams corrected by a gross field shift of −186 mm along the X-axis. (b) Vector plot after lateral horizontal shift correction showing the residual shift of individual dose spots. Shift magnitudes are indicated by the coloured vector arrows. (reproduced with permission from [9]).

Based on a custom-built semi-automatic method for 3D magnetic field mapping of large volumes, highly accurate magnetic field homogeneity measurements were performed by HZDR in the 0.32 T in-beam MRI scanner of their proto-type MRgPT facility. Work has started to optimize simple 3D dose distributions in the presence of the 0.32 T in-beam MRIs magnetic field by incorporating the measured 3D magnetic fringe field map in their treatment planning system. This allows to calculate the dose distribution of scanning pencil protons beams in presence of magnetic fields. In addition, in the future, the results of these measurements can be used to build an accurate Monte Carlo model to simulate the proton pencil beam transport through the magnetic field of the in-line MRI scanner, and to investigate the field characteristics of the deflected proton beam. Both are essential requirements for the development of MRgPT.

These measurement results can be compared with the results of the dose distribution calculated by the treatment planning system (see previous paragraph. This work was published in a peer-reviewed paper [9], and can be used in future definitions of reference fields for MRgPT.

Investigations on the application of passive detectors in a proto-type MRgPT facility demonstrates that important characteristics for alanine dosimetry (linearity, fading, and the impact of air gaps around the alanine pellet) remain unaffected by the magnetic field for measurements in MRgPT facilities. These measurements are the first attempts to realize traceability for dosimetry in a proto-type MRgPT facility based on passive detectors.

Measurements with cylindrical ionisation chambers have been carried out by DKFZ in a pencil beam scanning proton field in presence of the magnetic field of an electromagnet. By normalizing the ionisation chamber readings to the reading with no magnetic field present, the so-called $k_{B,M,Q}$ factor was determined. This was done for two different beam energies and for cylindrical chambers with different radii. The results show that the magnetic field may have a small (< 1 %) but significant impact on the response of cylindrical in presence of magnetic fields (

Figure 7). Part of these investigations focused also on the impact of the magnetic field on recombination corrections. Recombination correction factors are used in CoPs to correct the measured charge of an ionisation chamber for incomplete charge collection, which potentially may introduce non-linearities between measured current and dose-rate. This was investigated by so-called Jaffe plots (Figure 8) which was determined for three different magnetic field strengths and for no magnetic field present. The results show that the linear fit in the Jaffe plots are very similar for the four investigated conditions and therefore this work concludes that recombination corrections in proton beams de not depend on the magnetic field, which is a confirmation of previous work for photon fields.

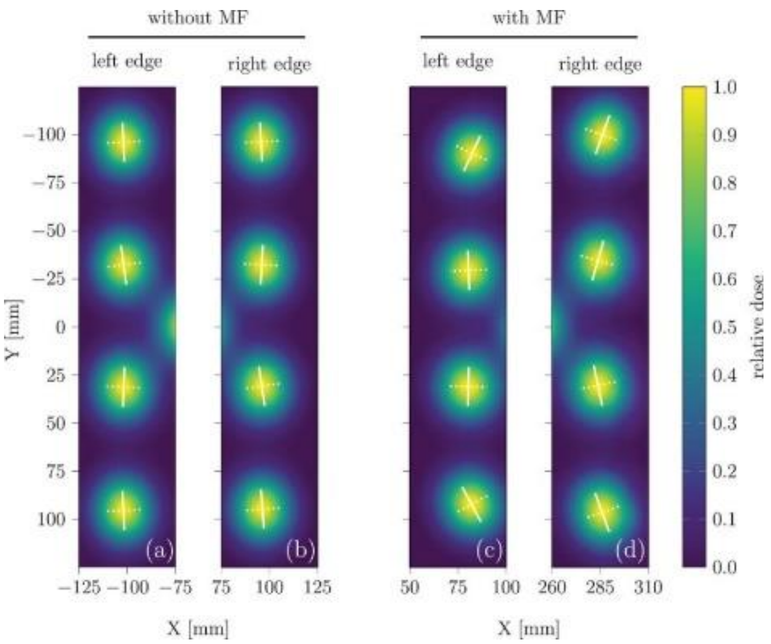


Figure 6 Beam's eye view of the 100 MeV dose spots on the left and right field edges of the 15 × 15 cm2 field measured without ((a) and (b)) and with ((c) and (d)) magnetic field at location D. The white cross-hairs represent the center position (X, Y),σ_{min}(dotted white line) and σ_{min} (solid white line) lateral standard deviation and the orientation angle θ of the dose spots. (reproduced with permission from [9]).

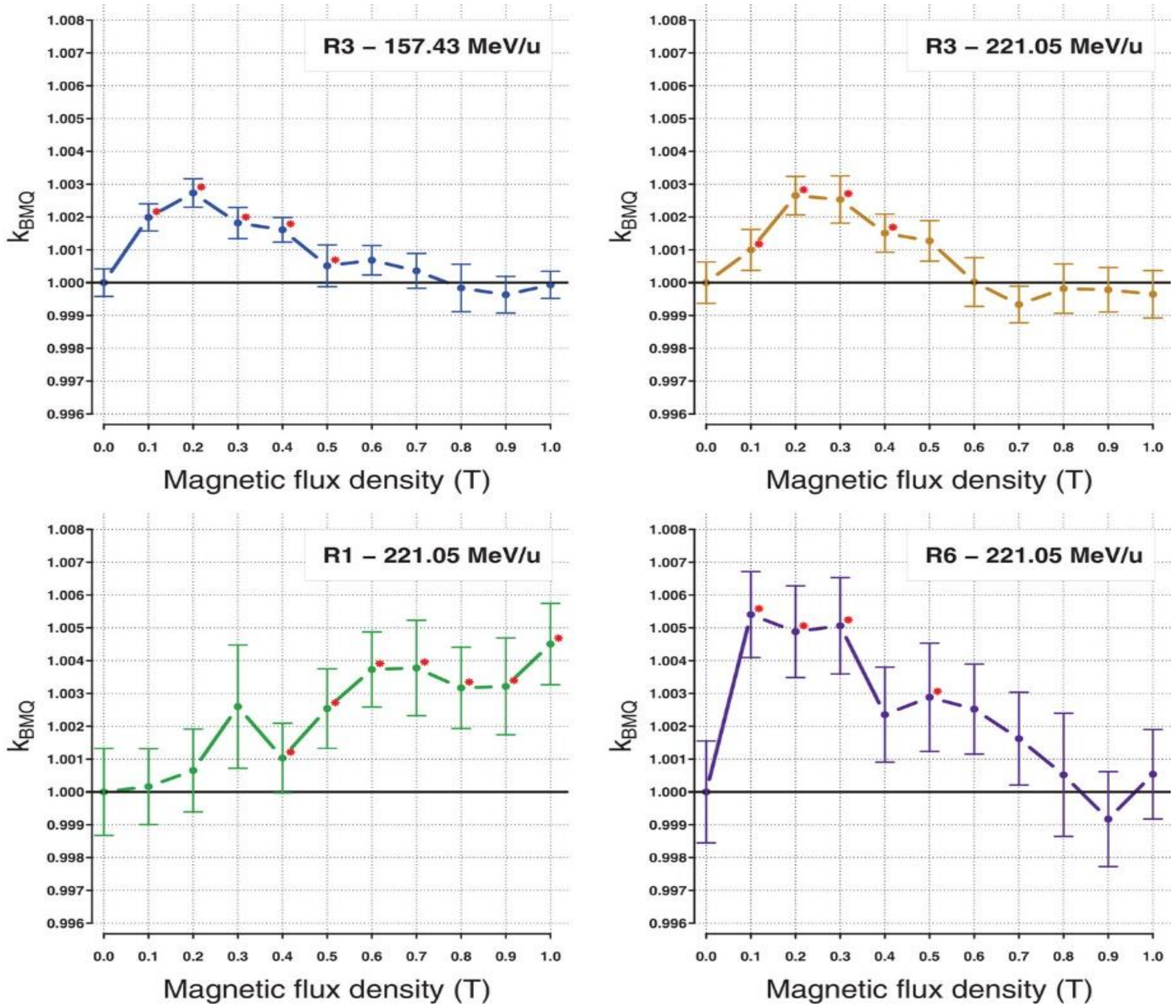


Figure 7 kB,M,Q values as function of the magnetic flux density, for the ionization chamber R3 at beam energies of 157.43 MeV/u (top-left) and 221.05 MeV/u (top-right), and for R1 (bottom-left) and R6 (bottom-right) ionization chamber for the beam energy 221.05 MeV/u. The error bars represent the standard error of the mean, and the red asterix (*) indicates a p-value ≤0.05 for the two sided Student's t-test, meaning that there is a significant effect of the magnetic field on the chamber response. (reproduced with permission from [8]).

The project partially achieved the objective and the key outputs are:
1. The presence of magnetic fields has a small (< 1 %) but significant effect on the response of ionisation chambers in scanning proton beams.
2. The presence of the fringe and the core magnetic field of an MRI scanner impact the position of the spot pattern, deforms the spot pattern and changes the shape of the sport in scanning proton beams for MRgPT.
3. Recombination effects in ionisation chambers for proton beams are not affected by the presence of the magnetic field.

4.3 Monte Carlo simulations of detector properties and radiation field characteristics (Obj.3)

Detectors properties

The predecessor project EMPIR 15HLT08 MRgRT has demonstrated the importance of accurate modelling of detector geometries for detector response simulation in the presence of magnetic fields. In particular, it has been demonstrated that the sensitive volume of ionisation chambers must exclude the so-called dead volume between the guard and the central electrode. A method to determine this volume by Finite Element Model (FEM) simulations was developed. While in the previous project this method was only applied for ionisation chambers used for reference dosimetry, in MRgRT-DOS this method was applied to ionisation chambers suited for small field dosimetry.

FEM simulations have been used by NPL and VSL to estimate the dead volume effects for a set of detectors for small field dosimetry

Figure 9 and Figure 10. These results show that small ionisation chambers used for small field dosimetry have a much larger dead volume compared to their total cavity volume than reference ionisation chambers. This emphasizes the importance of accurate determination of dead volume in ionization chambers in the context of chamber response simulations for MRgRT.

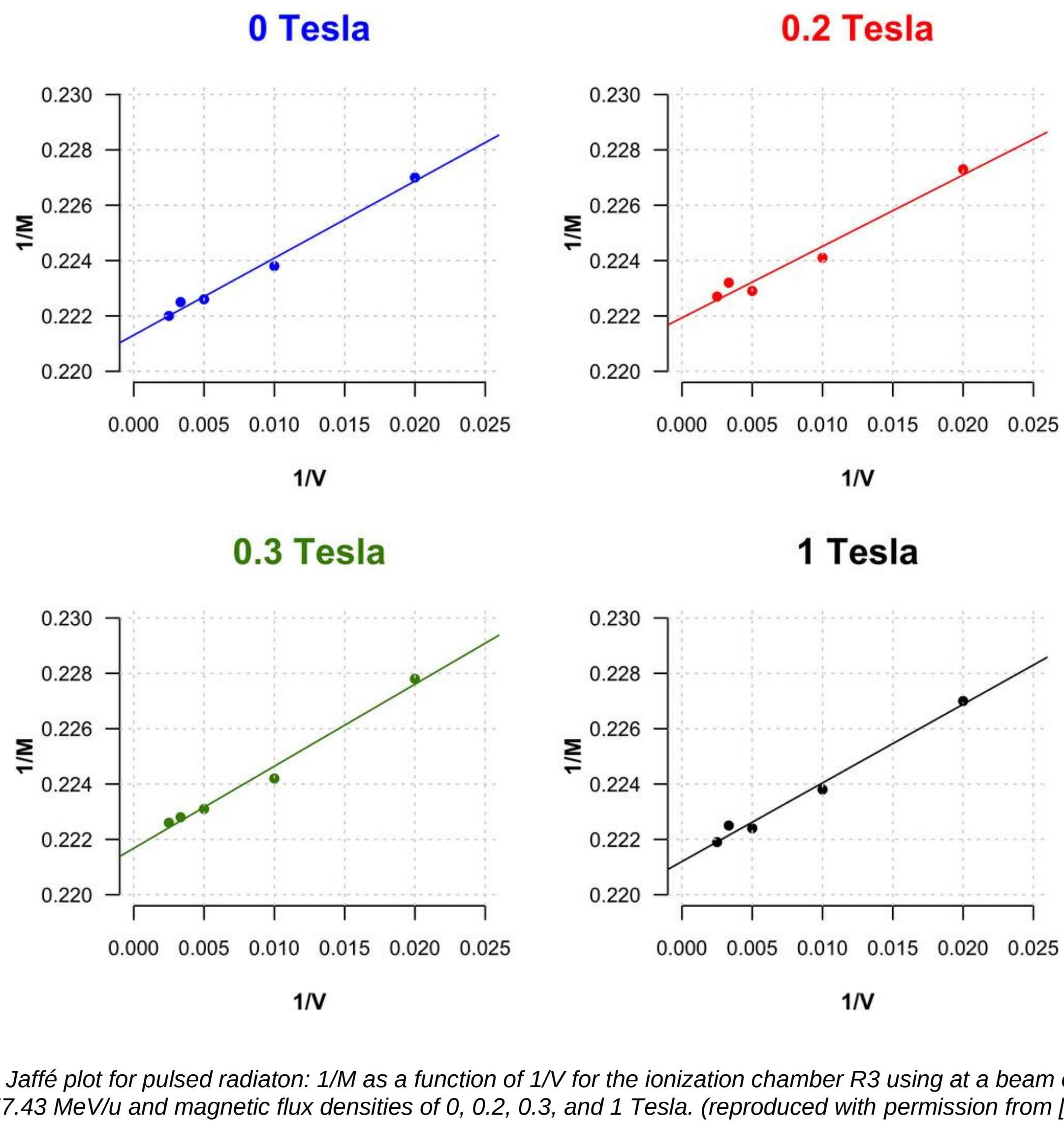


Figure 8 Jaffé plot for pulsed radiaton: 1/M as a function of 1/V for the ionization chamber R3 using at a beam energy of 157.43 MeV/u and magnetic flux densities of 0, 0.2, 0.3, and 1 Tesla. (reproduced with permission from [8]).

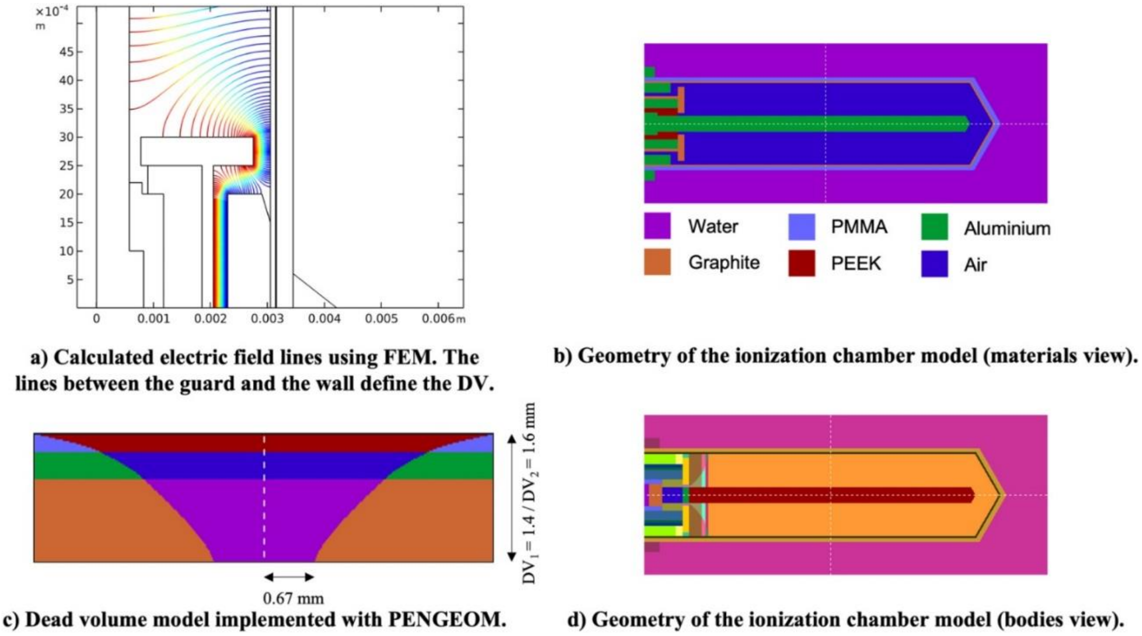


Figure 9 Model of the PTW 30013 chamber using PENGEOM. (reproduced with permission from [6]).

Simulated chambers responses were compared with measured chamber response as a function of the magnetic field strength in a Co-60 reference beam (Figure 11) by VSL. The results confirms that excluding the dead volume from the sensitive volume of the detectors results in improved agreement between measurements and simulations.

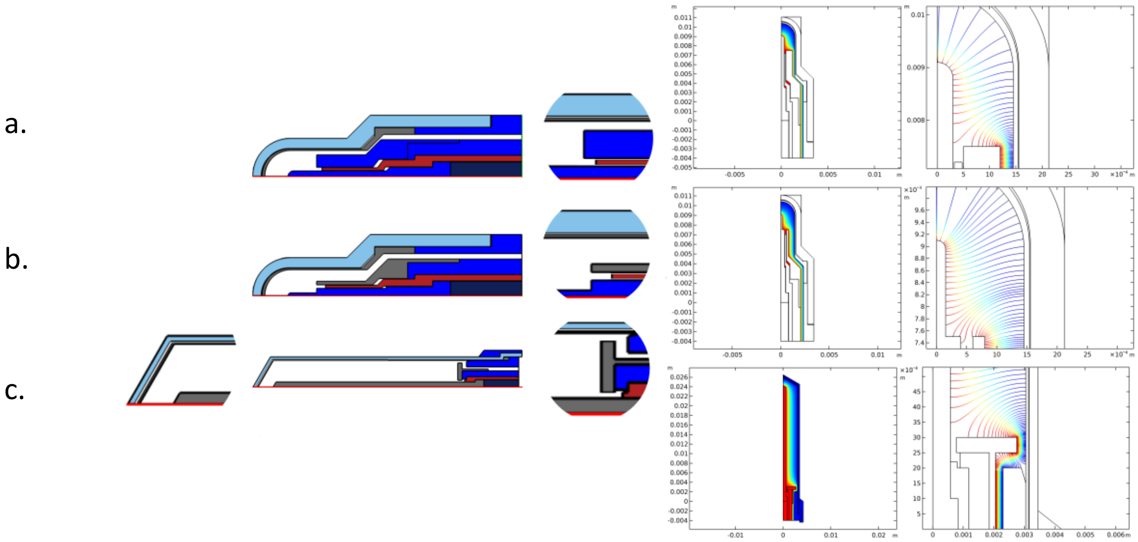


Figure 10 FEM simulations of the dead volume for the PTW 31016 (a.), the PTW 31022 (b.) and the PTW 310013 (c.)

Usually, in CoP the correction factors combine a number of effects into a single correction factor. Sometimes these factors are split into multiple factors that may give some idea on the impact of all contributions. For example, in the CoP TRS-398 for the k_Q factor of high-energy photon beams. An example such approach for output correction factors in presence of magnetic fields may be found in [2] .

In MRgRT-DOS a novel alternative approach was developed based on labelling particles. The method was used to determine which parts of ionisation chambers (such as central electrode or guard) of detectors contribute the most to the k_B factors. This method was applied in a study on $k_{B,Q}$ for reference ionisation chamber. The results of this study (Figure 12 and 12) conclude that chamber design and, to a lesser extent, choice of material affect $k_{B,Q}$, and that the contribution of the various parts strongly depends on the chamber orientation [6].

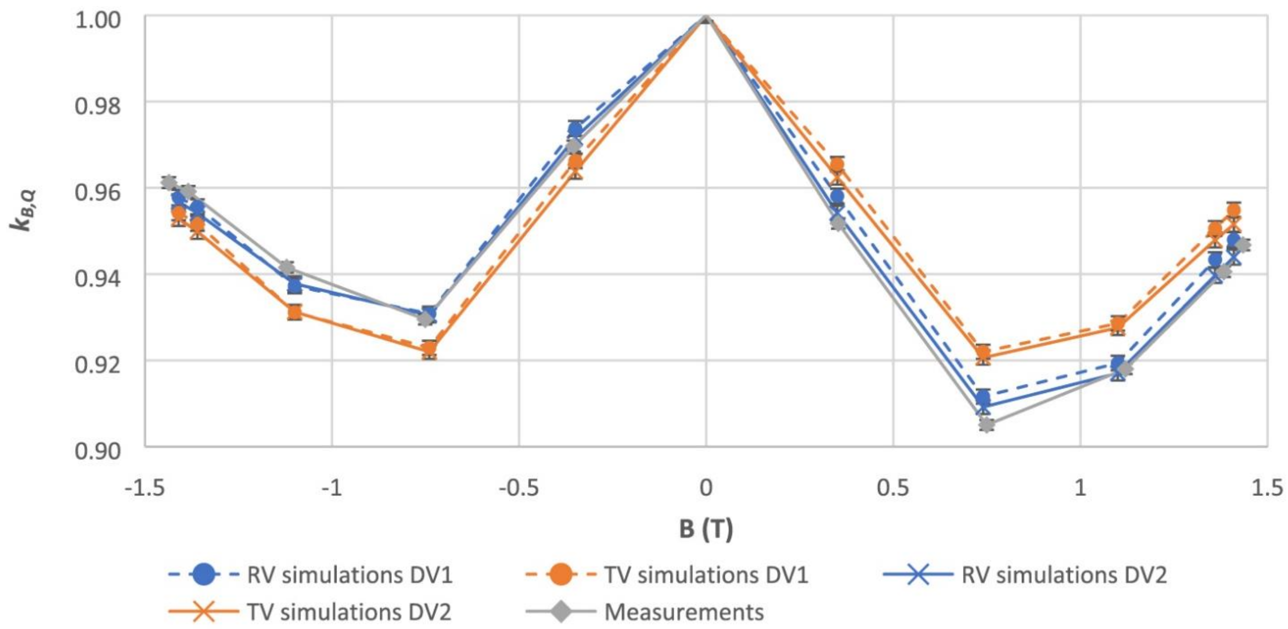


Figure 11 kB,Q correction factors as a function of the magnetic field for the 60Co source for α = 90° and α = 270°. The simulated values are for both the RV and the TV and for a geometries DV1 and DV2. (reproduced with permission from [6]).

Monte Carlo investigations by Uni-Oldenburg on the effective point of measurements demonstrate that the shift decreases in presence of magnetic fields with 40 % compared to the magnetic field-free case. This result allows for more accurate positioning of the detectors for measurements of relative dose profiles.

Radiation field characteristics

TRS-483 defines three criteria for categorising a photon field as a small radiation field.

1. Loss of lateral charged particle equilibrium (LCPE) on the beam axis
2. Partial occlusion of the source by the collimating system
3. Detector size similar to beam dimensions

Of these, the latter two are related to the properties of the linear accelerator and the detector respectively. Apart from field size, LCPE depends on the beam energy. For LCPE, TRS-483 provides an estimate of the smallest field size below which this effect will become sufficiently dominant as a function of beam energy represented by the beam quality specifier. This estimate follows from calculation of the ratio water kerma, K_w, and absorbed-dose-to-water, D_w as a function of field size. Deviation from a constant value is considered to be the point where a field becomes a small field.

VSL has simulated these ratio’s in presence of a magnetic field as function of radiation field size using the phase-space data of an Unity MR-linac beam. These results (Figure 13) demonstrate that for similar beam qualities as the 7 MV photon beam of the Unity MR-linac, the small field size limit is lower, when only considering LCPE, and that the presence of magnetic field increase this limit further.

Figure 12 Relative contribution of different solid components of the PTW 30013 chamber to $k_{B,Q} - 1$ *for the (a)* ^{60}*Co and the (b) MRL.* $B = 1.5$ *T for different orientations. (reproduced with permission from [6]).*

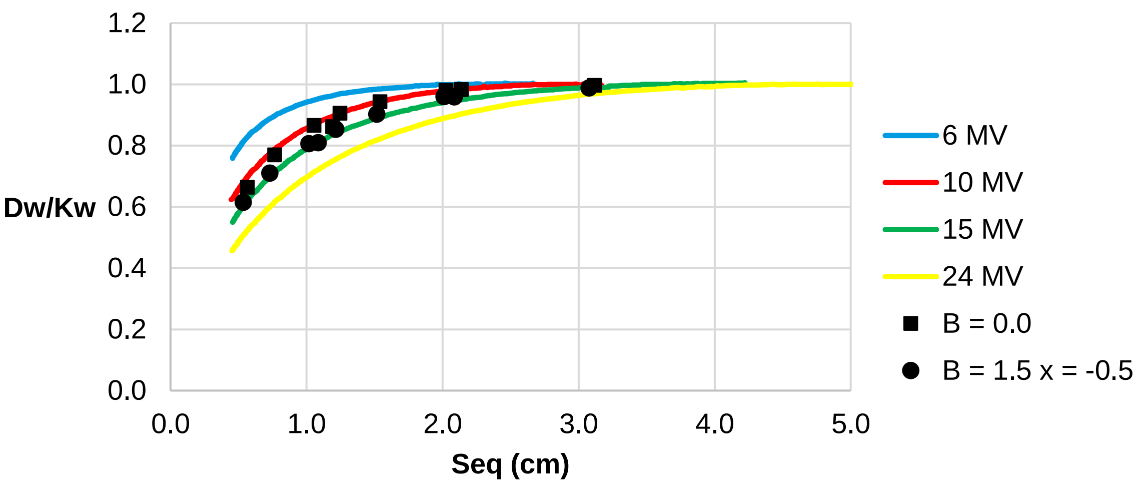


Figure 13 Ratios of dose-to-water and water kerma calculated for a set of field sizes for a Unity MR-linac with and without magnetic field present (circle and square data points). The data from Papaconstadopoulos which is also reported in TRS-483 is included for reference (coloured lines).

The project successfully achieved the objective and the key outputs are:

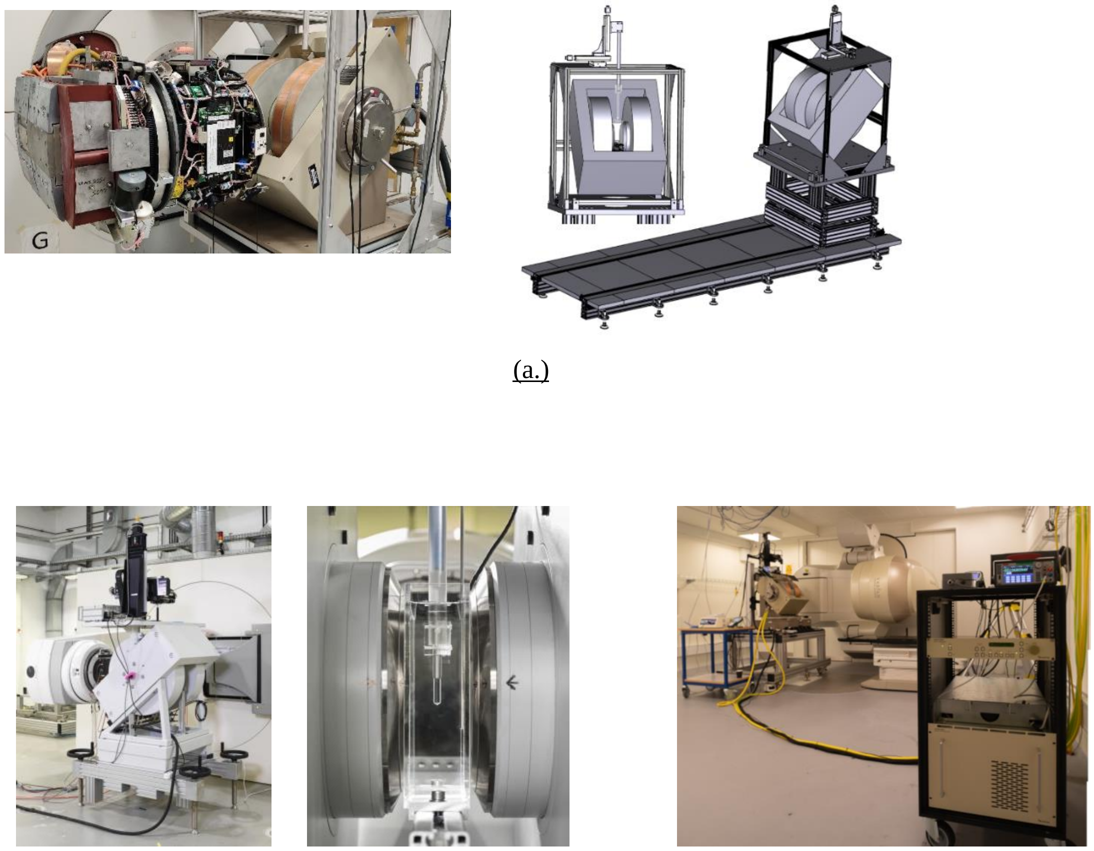
1. For ionisation chambers used for small field dosimetry the impact of excluding the dead volume from the sensitive volume is much larger than for reference ionisation chambers.
2. A new method to assess the relative contribution of detector components has been developed.
3. When considering only LCPE the small field size limit is higher for MR-linacs than for conventional radiotherapy beams. This limit is increased further when considering the magnetic field.

4.4 Experiments of detector properties and radiation field characteristics in MRgXT and MRgPT (Obj. 4)

Radiation field characteristics

Determination of correction factors or detector response accounting for the presence of the magnetic field can be based on either clinical MR-linac facilities or experimental facilities consisting of an electromagnet and a linear accelerator. The advantage of the latter is that the magnetic field can be easily modulated, which is difficult or impossible in MR-linacs which uses cryogenic superconductors. The disadvantage is that experimental facilities have (slightly) different characteristics such as: beam energy, Source-to-isocentre-distance (SID) and field shape. In particular for small fields these differences may become more pronounced. Another disadvantage of experimental facilities is the limited possibility to align the detector with the magnetic fields. Therefore, only perpendicular orientations can be used.

In the MRgRT-DOS project, PTB, DTU and NPL have realised several experimental facilities consisting of a linac and an electromagnet which have been optimized for small field dosimetry in presence of magnetic fields (Figure 14). Many data sets of output factors, cross- and depth-profiles have been measured using these facilities. To harmonize the methods and conditions among the various experimental facilities and MR-linacs used in the project, an overview of the experimental conditions have been drafted and the beam characteristics of all facilities have been summarized in a report. These data sets of beam characteristics can be used to compare the machine and radiation field characteristics between experimental facilities and commercial MR-linacs to assess their suitability as a test facility for small field dosimetry in MRgXT. An example of such a comparison between the experimental facility of PTB and the clinical MR-linac of UMCU is plotted in Figure 15.



(a.)

(b.)

(c.)

Figure 14 (a.) Experimental setup at NPL. An electromagnet is lifted on top of an aluminium table (right), which is placed on a rail to allow movement towards and back the linac gantry. The electromagnet has a fixed height with the centre of the poles being at the machine iso centre (SID = 100 cm). The electromagnet can move laterally by ±15 cm, to allow off axis measurements. Detectors can be placed between the poles of the electromagnet and irradiated with an x-ray energy of 6 MV using the conventional linac (Elekta Synergy). A water phantom, 7 cm x 21 cm x 18.2 cm, was designed to place each detector between the 7.3 cm gap of the magnetic poles, which gives maximum magnetic field strength of 1.55 T.

(b.) Experimental setup at PTB. An electromagnet (Bruker ER073W) is placed in front of an Elekta Precise accelerator (left). A small water phantom is positioned between the pole shoes of the magnet; an ionization chamber is mounted within this phantom and irradiated by a horizontal photon beam from the accelerator (right).

(c.) Experimental setup at DTU. The facility consists of a Varian Truebeam linear accelerator and a water cooled GMW 3473-70 electromagnet with a Danfysik System 8000 high-stability power supply. The accelerator can deliver seven different photon beam qualities: 4 MV, 6 MV, 10 MV, 15 MV, and 18 MV with flattening filter and 6 MV FFF and 10 MV FFF without flattening filter. A custom-designed water tank (99.5 mm wide) fits between the pole shoes of the electromagnet. In this configuration, the magnetic flux density can be adjusted in the range from 0 to +/-0.7 T. With a narrower distance between the poles, one can reach 2 T. Detectors can be placed radially and axially in the water tank using the PTW Trufix system. Detectors can be moved using three optical stages. The stages can perform profile scans vertically and horizontally. The electromagnet can be placed at the iso-center of the accelerator, but it is normally used at extended distance as to avoid any interference with the accelerator internal beam transport system.

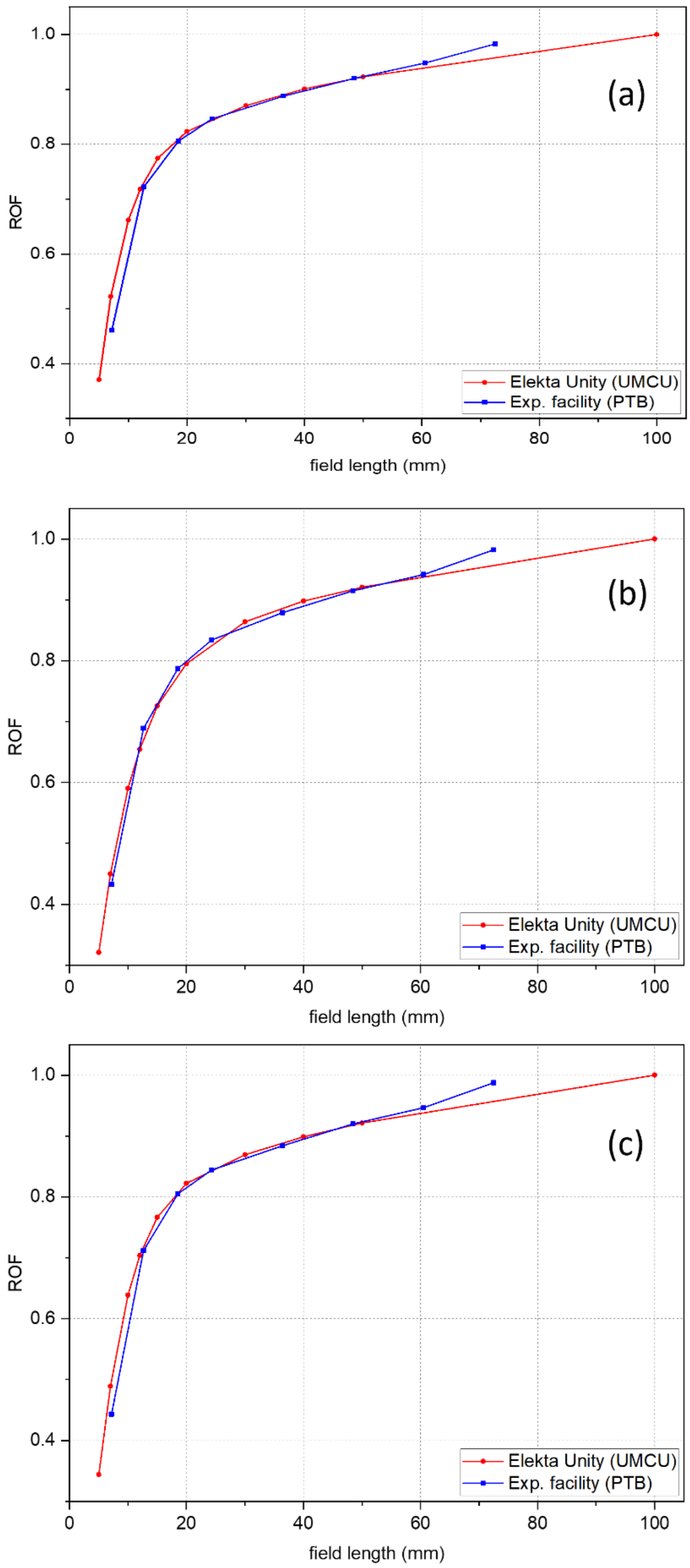


Figure 15 Comparison of the ROF curves obtained at the Elekta Unity MRI-linac and at PTB's experimental facility for an ionization chamber of type PTW 31022 positioned at CAX without the presence of a magnetic field (a), at CAX with a magnetic field B = 1.5 T (b) and at MAX with a magnetic field B = 1.5 T (c).

Using their characterised scintillator system (see paragraph *Detector properties* in section 4.4), DTU has measured the relative output factors in presence of magnetic fields at the maximum position of the radiation field (MAX). This was compared with the same data on the central axis of the field (CAX), without magnetic field present. The conclusion was that both datasets agree which suggests that for dose measurements at MAX the output correction factors are not or to a small extend affected by the presence of the magnetic field.

Detector properties

Scintillators are considered perturbation-free detectors and therefore are potentially an ideal detector for small field dosimetry. A disadvantage of these detectors compared to ionisation chambers and diodes is that the step between energy deposition in the sensitive volume and signal generation is affected by the characteristics of the radiation field. For this effect correction methods have been developed for conventional radiotherapy beams. DTU has characterised for their scintillator system the impact of the magnetic field on these corrections.

In addition, DTU has performed, time-resolved measurements using their scintillators in several clinical MR-linac facilities. These measurements (Figure 16) highlighted a dose transient at the start of every beam delivery, which until, was unnoticed by users of these facilities. This potentially affects homogeneity of dose delivery. These results have been published (https://doi.org/10.1016/j.radmeas.2022.106759).

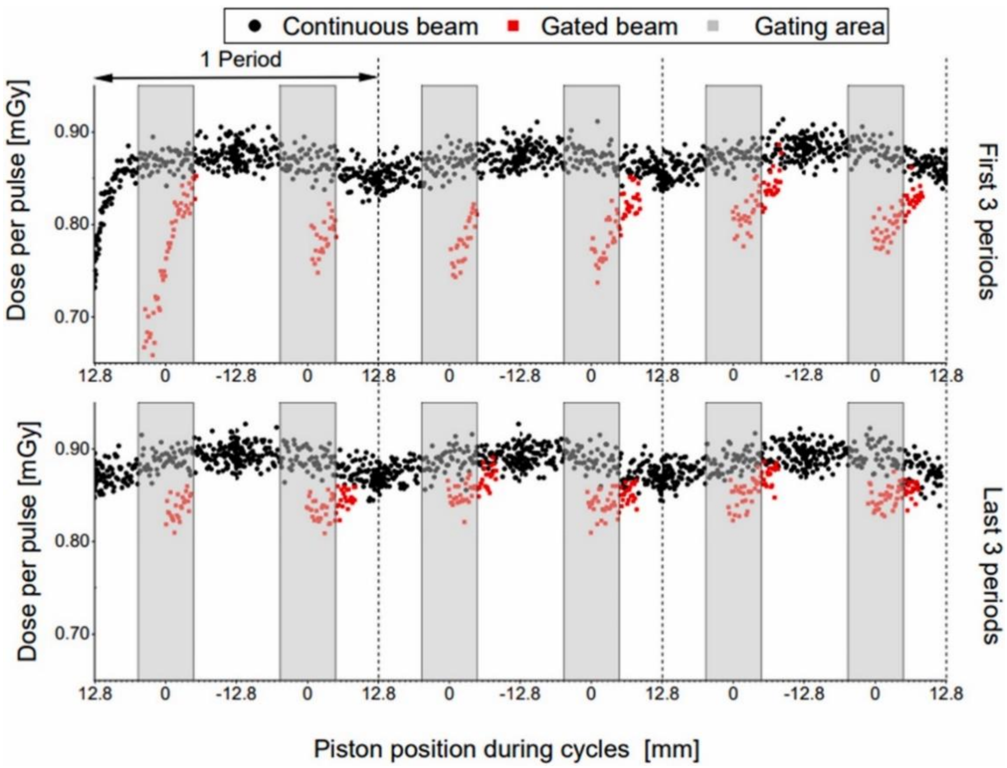


Figure 16 Differences in dose-per-pulse measured with and without gating (continuous beam) for a 4 s period. At the start of every beam-on, a dose transient lasting 1 s or more can be observed. The magnitude of the transient decreased over time during the treatment, which is evident from the gated beam when comparing the first three beam-on periods with the last three beam-on periods (reproduced with permission from [7]).

Radiochromic film is a detector which can measure 2D dose distributions with a high resolution. Since contact with water may have an impact on the results of the measurements with radiochromic films these films are often used in solid phantoms. In addition, measurements for treatment planning verification usually deploy anthropomorphic phantoms which include parts with a different density to mimic certain parts of the human body, such as lung and bone.

As part of a Research Mobility Grant (RMG), a researcher from VINS (Serbia) hosted at VSL has done investigations on the characteristics of radiochromic films for applications in solid phantoms. In particular, the investigations focussed on the impact of the magnetic field on the response of radiochromic film when applied *in phantom material with varying densities. To investigate this the $k_{B,M}$ parameters was determined as a function of magnetic field strength by measurements with the film in phantoms with varying densities (0.24, 1.19 and 2.2 g·cm^{-3}). The results (*

Figure 17) show that the highest impact was observed for phantom materials with a density close to that of lung tissue.

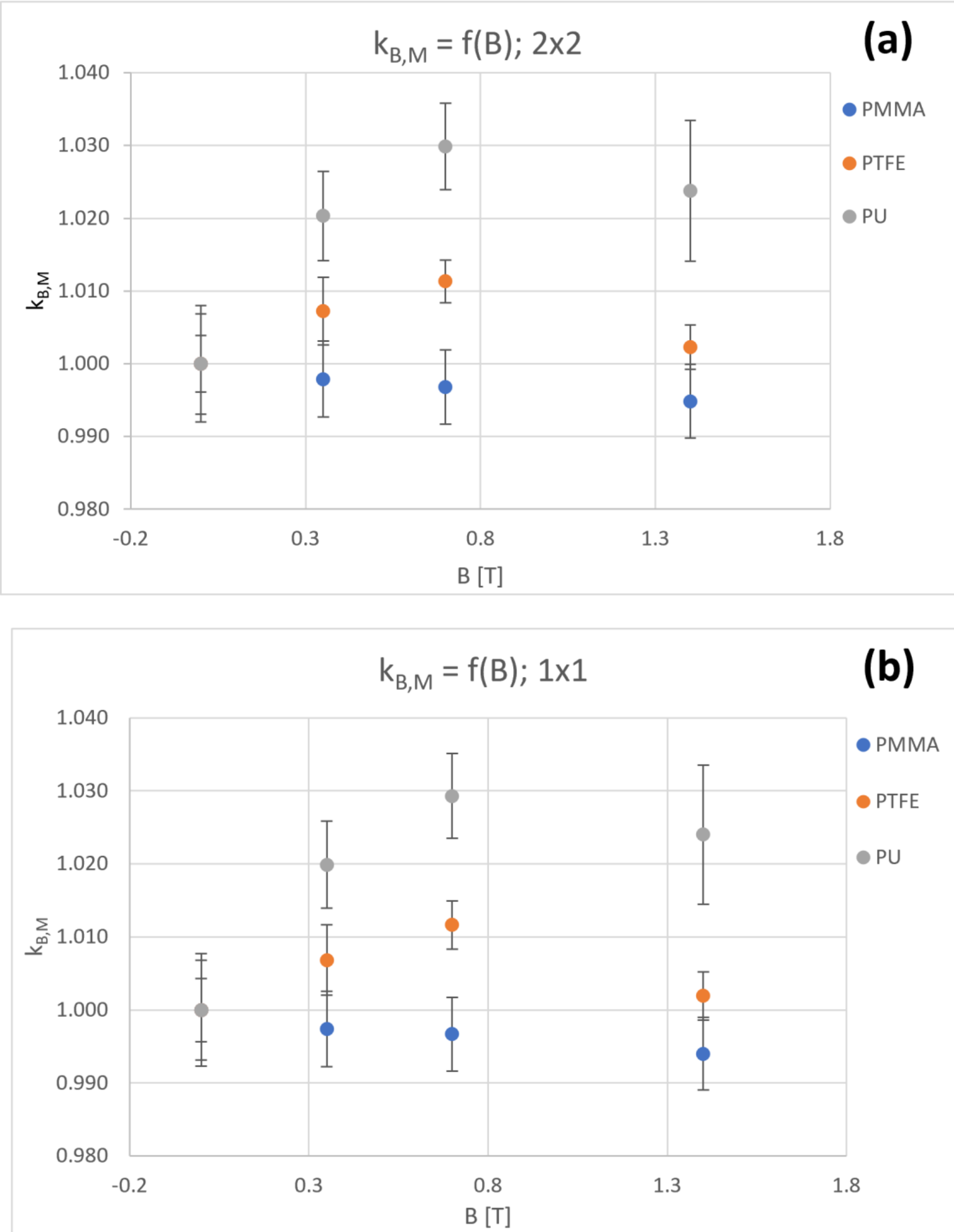


Figure 17 $k_{B.m}$ dependence of magnetic field strength for three different phantom materials for ROI 2x2 cm^2 (a.) and 1x1 cm^2 (b.).

The project successfully achieved the objective and the key outputs are:

1. Three experimental facilities for the characterisation and the determination of correction factors of detectors have been realized.
2. Perturbation-free scintillator systems have been characterised for application in presence of magnetic fields.
3. Output factors measured at MAX are independent on the magnetic field
4. Impact of phantom material density on radiochromic film response change as a function of magnetic field strength is maximal for densities similar to those of lung tissue.

5 Impact

The project had impact on SDOs, the growing number of hospitals beginning to introduce MRgRT and the medical device industry; more specifically manufacturers of dosimetry equipment and MRgRT facilities. This will be of great benefit to a large population of patients in Europe and worldwide. The existing website of the previous project 15HLT08 MRgRT has been updated with results from the MRgRT-DOS project https://mrgrtmetrology.com/. The consortium has published ten peer-reviewed publications (3 more have been submitted, of which one has been accepted) and 27 conference contributions on dosimetry for MRgRT.

An online satellite symposium was organised in connection to the MRinRT 2021 congress in April 2021 with more than 200 participants. Participants from SDOs, hospitals and industry attended the symposium with many presentations from the MRgRT-DOS consortium. The symposium was used to inform the participants in general and stakeholders specially on the progress of MRgRT-DOS and developments since the previous symposium organised in the previous project 15HLT08 MRgRT.

Two online stakeholder meeting have been organised with the project's stakeholder committee including key representatives from SDO's, hospitals and industry. The work of the project was presented to the stakeholders and the current knowledge gaps in dosimetry for MRgRT were identified in a moderated discussion session. The information from this discussion session allows to consortium to get a more balanced view on the needs for the difference stakeholder groups. For example, hospitals expressed their need for methods and data for small field dosimetry in MRgXT, while SDOs do not have established working groups on this specific topic.

Information on the project has been shared in four standards committees (AAPM TG 351, ESTRO ACROP Physics, NCS MR-linac QA, DIN). The results of the project have been presented at the annual meeting of EURAMET TC-IR in February 2022. The consortium is preparing an on-line webinar which will be organized in collaboration with the BIPM and CCRI on September 12 2023. The webinar has been published online as part of the CCRI webinar series and is available via https://youtu.be/BkWrPrTo-6Y?si=H0FxmKVObxsKs32t.

Part of the work being carried out in the project demonstrates the negative impact of small air volumes in ionisation chamber for small field dosimetry in presence of magnetic fields. Based on these results, a manufacturer of dosimetry equipment has started to optimise their design of ionisation chambers for measurements in presence of magnetic fields and has already completed this for two types of chambers.

The review paper [1], named as Reference dosimetry in MRI-linacs: evaluation of available protocols and data to establish a Code of Practice, is considered as the basis of future Codes of Practice for reference dosimetry in MRgXT.

Impact on industrial and other user communities

The project has developed traceable methods to determine detector type specific output correction factors for small field dosimetry in MRgXT and it has determined a dataset of detector type specific output correction factors. Furthermore, it has developed a methodology consistent with TRS-483 for small field dosimetry in MRgXT facilities with an uncertainty similar to the uncertainty reported in TRS-483 for small field dosimetry in conventional radiotherapy (2.0 %).

These results will accelerate the development of CoPs for small field dosimetry in MRgXT by SDOs. The methodology developed in MRgRT-DOS for small field dosimetry in square fields was shown to yield an uncertainty of 2.0 % for field sizes down to 0.5 x 0.5 cm^2. This methodology was presented to the stakeholder committee in the last stakeholder meeting (Oct. 2022). Final results of this method were presented at the 4th ECMP congress in Dublin and the ESTRO congress in Vienna. A publication is in preparation.

The experimental setups for small field dosimetry in the presence of magnetic fields characterised in the project enable the assessment of detector performance and suitability in well-defined test conditions. This allows manufacturers of measurement equipment to assure the quality of their products for application in small-field dosimetry in MRgRT. In addition, it will enable and support manufacturers of radiotherapy equipment, by demonstrating that MRgXT and future MRgPT facilities are compliant with regulatory criteria. A short overview of preliminary results from the various experimental and clinical facilities was presented to the stakeholder committee in the 1st stakeholder meeting.

The project has developed traceable dose measurement for proton beam dosimetry in the presence of magnetic fields. This will enable industry and research groups to show the feasibility of dose delivery of prototype MRgPT devices. The involvement of industry in the stakeholder committee and a collaborator from a research centre active in MRgPT enhances the dissemination of these methods. Therefore, this methodology will impact the future development of documentary standards in MRgPT. At the last PTCOG meeting a presentation on ionization chamber response to protons in presence of magnetic field was given. Overall, the results of this project have been disseminated to the medical physics community, via publications, the webinar, and an organized symposium.

Impact on the metrology and scientific communities

European National Metrology Institutes (NMIs) are global leaders in the field of dosimetry for MRgRT. This project has improved their existing measurement infrastructure for dosimetry in MRgRT, by extending the range of application in MRgXT dosimetry to small field dosimetry and to dosimetry for MRgPT facilities. Results, capabilities and improved knowledge has been disseminated to the European and international metrological community via their annual meetings. At the meeting of Euramet TC-IR in 2021, 2022 and 2023 and the CCRI meeting of 2021 an overview of the achievements of MRgRT-DOS has been presented. In the framework of an RMG, a guest researcher from a European DI outside the consortium has worked on the MRgRT-DOS project.

Several university groups are exploring new MRgPT facilities by the integration of proton beams with MRI scanners. The consortium has intensively collaborated with one of these groups (Medical University of Vienna) and therefore this project contributed to and support the scientific activities in this field. Furthermore, CoPs for dosimetry in radiotherapy are based on a vast amount of scientific publication. Given the lack of scientific publications on small field dosimetry for MRgXT and dosimetry for MRgPT, the publications of this project will impact the development of CoPs for small field dosimetry in MRgRT considerably.

Impact on relevant standards

The project has developed a methodology for and has determine detector type specific correction factors for small field dosimetry in MRgRT. Via active participation in standard committees of AAPM, NCS ESTRO and DIN and by active engagement of SDOs in the stakeholder committee (IPEM, IEC, IAEA) the consortium has ensured that the results will be used in future standards for small field dosimetry in MRgXT and for the future MRgPT, in line with IAEA TRS-483. Consortium partners actively participate in the working groups ESTRO-ACROP physics, NCS subcommittee on MR linac QA, AAPM TG-351 and DIN NA 080-00-01 AA. The SDOs related to these working groups participate in the stakeholder committee.

Longer-term economic, social and environmental impacts

The rough estimate of the 1.4 million patients undergoing radiotherapy in Europe annually, that will benefit from MRgRT in the long-term, is >50 %. In addition, MRgRT will enable non-invasive treatments on a range of cancers, for which conventional radiotherapy, to date is inadequate, e.g., lung and pancreatic cancers.

MRgXT is a technique clinically introduced only recently by pioneering European hospitals and early adopters. Currently, the broader hospital community starts with the clinical implementation of MRgRT and the adoption rate will increase. The dissemination of the metrological research from this project via peer-reviewed publications, documentary standards and potential commercialisation of methodologies, will enhance the safe introduction of MRgXT and accelerates clinical acceptance by the broader community of European hospitals.

Proton therapy is considered as the treatment of choice in the field of paediatric oncology, and for a selected group of adult patients. MRgPT which combines superior soft tissue contrast from MR images with superior dose distributions from proton beams is considered the next major advancement in radiotherapy in the mid and long-term. The metrological research carried out in the project will be a key enabler for future translation of current prototyping efforts of manufacturers to a clinical setting. As such, this project enhances improved patient care in radiotherapy and future innovations in radiotherapy. Therefore, it will improve the quality of life of a large group of patients.

Market sales of MRgXT facilities have continuously increased since CE mark approvals mid-2016 and mid-2018 and represents a total revenue of more than 800 million Euro. Therefore, the economic value of MRgRT facilities is high. The outcome of this project and the dissemination of the results via peer-reviewed publications and documentary standards will enhance the speed of the commissioning process, increase the safety of the clinical implementation and accelerate propagation of MRgRT into the market.

6 List of publications

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[4] Pojtinger, S., Nachbar, M., Ghandour, S., Pisaturo, O., Pachoud, M., Kapsch, R-P. and Thorwarth, D., *Physics in Medicine & Biology 65 (2020)*, Experimental determination of magnetic field correction factors for ionization chambers in parallel and perpendicular orientations. https://doi.org/10.1088/1361-6560/abca06

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[6] Navarro Campos, J., de Pooter, J.A., de Prez, L.A., Jansen, B. *Physics in Medicine & Biology 67 (2022)*, The impact of ion chamber components on $k_{B,Q}$ for reference dosimetry in MRgRT. https://doi.org/10.1088/1361-6560/ac77d0

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[8] Mathieu Marot, Sonja Surla, Elisa Burke, Stephan Brons, Armin Runz, Steffen Greilich, Christian P. Karger, Oliver Jäkel, Lucas N. Burigo, *Medical Physics* (2023) Proton beam dosimetry in the presence of magnetic fields using Farmer-type ionization chambers of different radii. https://doi.org/10.1002/mp.16368

[9] Benjamin Gebauer, Jörg Pawelke, Aswin Hoffmann, Armin Lühr, *Medical Physics (2023)* Experimental dosimetric characterization of proton pencil beam distortion in a perpendicular magnetic field of an in-beam MR scanner. https://doi.org/10.1002/mp.16448

[10] M F Klavsen, C Ankjærgaard, K Boye, C P Behrens, I R Vogelius, S Ehrbar, M Baumgartl, C Rippke, C Buchele, C K Renkamp, G V Santurio and C E Andersen, Biomedical Physics & Engineering Express (2023) Accumulated dose implications from systematic dose-rate transients in gated treatments with View ray MRIdian accelerators. https://doi.org/10.1088/2057-1976/acf138.

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/