MRgRT Metrology

15HLT08 MRgRT

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Publishable Summary for 15HLT08 MRgRT Metrology for MR guided Radiotherapy

Overview

Cancer patients are treated with radiotherapy in which megavolt (MV) photon beams are used to deliver a high dose of ionizing radiation to target and kill cancerous cells. **MR-guided radiotherapy (MRgRT),** the simultaneous use of Magnetic Resonance (MR)-imaging and MV photon beams allows clinicians to see what is being treated and to adapt and further optimise the treatment and is next in advanced radiotherapy. The project has improved metrological capabilities in radiation dosimetry and imaging by the investigations and developments on a methodology for reference dosimetry and by the development of quality assurance procedures for clinical MRgRT treatments. This is not only vital for the safe **clinical implementation** of MRgRT but also for future **innovations** in MRgRT.

Need

In 2012, cancer incidences in the European Union were approximately 2.6 million people (~0.5 % of the population) per year. The devastating consequences of this disease affected the daily life of a large proportion of the European population with roughly half of these patients being treated using radiotherapy.

In Europe and worldwide several manufacturers and academic hospitals have been developing MR guided radiotherapy facilities. The feasibility of MRgRT was demonstrated by the first successful treatments in 2014. The benefits of MRgRT are:

- an increased accuracy in defining the contours of tumour, organs and other healthy tissue.
- avoidance of additional exposure to harmful radiation from diagnostic imaging modalities (e.g. CT) currently used.
- the ability to image motion, caused by internal movements of the patient (e.g. breathing, swallowing), during treatment. This allows adaptation and optimisation of the dose during the treatment.

The magnetic field cannot easily be switched off for these MR-guided radiotherapy modalities; therefore measurement of the radiation dose (dosimetry) needs to be performed in the presence of the constant magnetic field. Under this condition, both the detectors used for dosimetry and the dose distributions are highly influenced by the magnetic field. Since the underlying physical mechanisms are not well understood, **traceability** for radiation **dosimetry** and adequate **knowledge of detector characteristics** is lacking and no Codes of Practice (**CoP**) are available for reference dosimetry and measurements of the **radiation field characteristics**. Therefore, medical physicists were not able to accurately calibrate the radiation field and characterise the radiation fields in MRgRT for treatment planning. Furthermore, **the accuracy of the Monte Carlo** algorithms required for the calculation of detector response and dose distributions in the presence of magnetic fields needed to be improved further.

To guarantee that the dose distribution is delivered to the patient as intended in treatment planning, the medical physicists and clinicians required Quality Assurance (**QA) procedures** and **MR-compatible dynamic phantoms** to verify the dose delivery under static and dynamic conditions, and **methods to determine appropriate safety margins** around the tumour.

Objectives

The overall aim of the project was to develop the metrological capacity in dosimetry and imaging required for the safe **clinical implementation and application** of MR guided radiotherapy and to support future **innovations** in MRgRT. The specific scientific and technical objectives of this project were:

1. To develop a metrological framework (primary and secondary standards) for traceable dosimetry under reference conditions for MR guided radiotherapy. This shall include the determination of input data and establishing a formalism for reference dosimetry including reference conditions for future **dosimetry protocols** (**CoPs**).

2. To develop methodologies for measurement of treatment planning system (TPS) input data for MRgRT. This should include determination of **detector characteristics** for commercially available detector systems and secondary standards in hybrid fields, and **characterisation of the radiation field** based on measurements and Monte Carlo modelling.

3. To develop methodologies to assess the **accuracy of the Monte Carlo** based radiation transport algorithms in external magnetic fields.

4. To evaluate MR based dose delivery under static and dynamic conditions. This should include:
    a. determination of associated geometrical uncertainties of standardised MR sequences and accurate registration methods, for the assessment of the overall geometrical uncertainty;
    b. development of **MR compatible phantoms** for **quality assurance** of dose distributions for static and dynamic conditions;
    c. development of reliable MRI target and organ motion tracking methods.
    d. evaluation of the effect on the residual uncertainties on actual treatment plans **to determine appropriate safety margins** around the tumour.

5. To facilitate the take up of recommendations for dosimetry and MR related quality assurance of MR guided radiotherapy developed by the project by clinicians and industry in order to enable hospitals to perform **quality assurance** based on traceable measurements and support improvements for dosimetry in MRgRT.

Progress beyond the state of the art

This project went beyond the state of the art by determining input data, (mainly k_B, the correction factor for the presence of the magnetic field) based on water calorimetry and Monte Carlo simulations, for a CoP and by the proposal and validation of a formalism for reference dosimetry in MRgRT with a target uncertainty of 2 %.

Radiotherapy treatments rely heavily on TPS, which are used to calculate and optimise the dose distribution. TPS dose calculation algorithms need accurately measured input data (such as lateral dose profiles). This project went beyond state of the art by delivering detector characteristics, which enables adequate selection of detectors for the measurement of TPS input data for MRgRT.

Monte Carlo radiation transport codes have been benchmarked to a high accuracy for detector response simulation in conventional radiotherapy, both with experiments and for internal consistency. For application in the presence of a magnetic field both benchmarks are lacking. This project went beyond state of the art by benchmarking, both for internal consistency and experimentally, several general-purpose codes in realistic conditions for the simulation of radiation transport in the presence of magnetic fields.

The implementation of MRgRT will progress clinical workflows towards image-based adaptive treatment, which will compensate for changes in the anatomy (due to breathing or deformation of organs and tumour) using feed-back loops in which the image information is fed back into the TPS. This project went beyond state of the art by developing, QA procedures for single steps (e.g. isocenter alignment) as well as integrated end-to-end tests for image-based adaptive treatments. This requires MR-compatible static and dynamic phantoms. In addition, a simulation platform will be developed to evaluate the impact of the overall geometrical and dosimetrical uncertainties for individual patients, such that clinicians and medical physicists can determine adequate safety margins for MRgRT.

Results

Objective 1: Reference dosimetry

A water calorimeter was successfully commissioned as primary dosimetry standard for MR-linacs [1]. The optimized calorimeter was tested and applied by VSL in the first world-wide measurements with a water

calorimeter in the presence of a magnetic field [2]. In these measurements the calibration coefficients of a set of ion chambers was determined against the water calorimeter in an MR-linac. These chambers have been used later on in the preparation of the first clinical treatments with an MR-linac [3]. In a separate measurement, reference dosimetry based on these calibration coefficients has been compared a completely independent indirect method. Both methods agree within 0.5%.

A formalism for reference dosimetry in MRgRT facilities was developed [4]. The new formalism describes how existing formalisms for reference dosimetry in conventional radiotherapy can be extended to application in MR-linac facilities. The most important aspect of the formalism is the addition of a separate chamber-type specific correction factor, k_B, which corrects for the presence of the magnetic field.

Four independent methods have been developed in this project to measure these k_B correction factors for a set of ionisation chambers:

1. A method based on the water calorimeter. With this method ionisation chambers are directly calibrated against the primary standard in an MR-linac with and without magnetic field present [2].
2. An indirect method. With this method the calibration coefficient of an ionisation chamber at zero magnetic field is determined at NPL as a function of $TPR_{20/10}$ and interpolated to the value measured in an MR-linac. The calibration coefficient in the presence of magnetic field (i.e. directly in an MR-linac) is obtained using alanine as a transfer standard. The effect of the magnetic field on alanine response is taken into account and corrected for in the transfer.
3. A method based on a combination of an electromagnet and a conventional linear accelerator (see Figure 5). With this method the response change of ionisation chambers is measured with varying magnetic field strength. The change in the dose at the point of measurement is calculated by means of Monte Carlo simulations. Combining this with the response change delivers the k_B as a function of magnetic field strength [5].
4. Method based on chamber monitor ratio in MR-linac facility. This method uses a monitor positioned outside the magnetic field of the MR-linac to monitor the beam output. The ionization chamber is positioned inside the MR-linac. The change in D_w is determined in a similar way to method 2. From this data, the k_B of the chamber can be determined for the MR-linac beam [4].

Type specific correction factors for ionization chambers can only be applied if the intra-type variability is sufficiently low. Therefore, additional investigations have been carried out in the project to determine the variation in k_B among chamber of the same type. This was done for different orientations and for two sets of commonly used ionisation chamber types for reference dosimetry. It demonstrated that this intra-type variability was within 0.2% for the investigated chamber types [6], which is sufficient for application of type specific k_B correction factors. Overall it has resulted in a data-set of measured chamber-type specific k_B factors with a level of consistency of less than 1.0 %, which is adequate as input for a code of practice for reference dosimetry.

The dependency on the magnetic field of several characteristics of ion chambers were investigated. As part of this, saturation and polarity effects, two commonly known effects in ion chambers, have been investigated and shown not to change with the magnetic field strength. A new discovery in the project was the increased influence of dead volumes in ionisation chambers in the presence of magnetic fields [7]. This had a considerable impact on performing chamber response Monte Carlo simulations in the presence of magnetic fields. Therefore a new method to determine the size and shape of this dead volume by Finite Element Methods (FEM) simulations [8] was developed. Its impact on improved accuracy to simulate detector response changes in the presence of magnetic fields was successfully demonstrated. Overall, it has been concluded that the developed methods and measured dataset allows to perform reference dosimetry in MRgRT with a similar uncertainty as for conventional radiotherapy. Therefore, objective 1 was fully achieved.

Objective 2: Measurement of TPS input data

Based on measurements in WP2 at two different types of clinical MR-linac facilities and at one experimental setup consisting of a linear accelerator and an electromagnet, a comprehensive dataset of radiation field characteristics in the presence of magnetic fields was produced. For the Elekta MR-linac this comprehensive dataset has become part of the standard beam data collection set and requirements for these facilities and has been published as peer-reviewed publication. This dataset gives in-depth insight in the dependence of several field characteristics on the magnetic field strength and beam quality, in the differences between clinical facilities and whether experimental setups can serve to simulate the radiation fields of MR-linacs. In addition

investigations on other beam characteristics that are not significant were performed, such as the increased out-of-field surface dose [9,10]

Magnetic field dependency of point, 2D and 3D detectors commonly used in relative dosimetry has been investigated [11]. Furthermore, the feasibility of detectors for specific relative dose measurements required for the TPS input dataset has been studied. This has resulted in a table that show which detectors are suited to measure specific beam characteristics needed to measure TPS input data. Many of these results have been used in the preparation for the first clinical treatments in the MR-linac in the so-called first in men (FIM) study. This objective was fully achieved.

Objective 3: Monte Carlo (MC) simulations in the presence of magnetic fields

Three of the most used Monte Carlo algorithms for simulation of detector response; EGSnrc, PENELOPE and Geant4, have implemented the magnetic field. Depending on the implementation one or more simulation parameters steers the accuracy of the simulation of radiation transport in magnetic fields. The accuracy of these codes for detector response simulations in the presence of magnetic fields and its dependence on these simulation parameters has been poorly investigated due to the lack of both theoretical and experimental benchmark methods. Recently a test to benchmark (the so-called Fano test) this accuracy by theoretical means has been developed. This test was applied in this project to these three Monte Carlo algorithms for detector response simulations. Furthermore, facilities for experimental benchmarking of these simulations didn't exist and have been developed and optimized in this project. As part of this project a Fano test was designed to assess the accuracy of the three aforementioned Monte Carlo codes. This Fano test uses a consensus geometry of an ionisation chamber which is close to the geometry of real ionisation chambers The test was performed for at least two spectra of the radiation field (6 MV and 8 MV linac beam) and for at least two magnetic field strengths; 0.0 T and 1.5 T. Overall it was concluded that EGSnrc and PENELOPE were able to pass the Fano test within 0.1%. GEANT4 was able to pass the Fano test within 0.6%. This depends on the applied simulation parameters as well as on the orientation of the magnetic field with respect to the chambers.

Experimental benchmarks have been developed in this project and were applied to a Farmer-type ionisation chamber. The benchmarks are based on a setup consisting of a linac or a Co-60 source with an electromagnet Using a modified water phantom, an ionisation chamber can be positioned at a reference distance and depth from the radiation source. The ratio of the charge for a magnetic field strength normalized to the change without magnetic field is calculated for the comparison with the Monte Carlo simulated response changes. The geometry modelled in the Monte Carlo code consists of the phantom, the ion chamber based on the manufacturer blueprints and the pole faces. The beam is modelled based on the phase space files already available of the irradiation facilities. From these experimental benchmarks it can be concluded that the level of agreement between measurements and simulations is in the order of 0.3 %, which for the main part can attributed to intra-type variability of the ionisation chambers. Therefore, objective 3 was fully achieved.

Objective 4: Evaluation of MR based dose delivery

Significant progress has been made towards improving 2D and 3D dosimetry methods for the measurement of clinical dose distributions [12]. A Polymer gel (PG) and Fricke gel have been shown to agree within the given uncertainties. The combination of TLDs and PG was shown to be a very promising method for measuring the absolute 3D dose distributions[13].

As part of this project several phantoms have been developed:

1. A static deformable MRI compatible phantom
2. An MR-compatible dynamic phantom [14]
3. A static phantom for testing imaging and irradiation isocenter accuracy as well as image distortions in was developed. The phantom is visible both on CT and MRI and contains a 3D polymer dosimetry gel container to allowing for 3D evaluation of "star-shot"-irradiations[15].

Phantom 3 has been applied for machine quality assurance on MR-linac. The accuracy of isocenter alignment in the three directions was shown to be within 1mm. MR image distortion was shown to be less than 1 mm for within 140 mm distance from the isocenter [16]. Both values are clinically acceptable.

Using PG and phantom 1, the first end-to-end test for inter-fraction adaptive treatment workflows was developed. Based on phantom 1 and an existing anthropomorphic porcine lung phantom the first end-to-end tests for intra-fraction adaptive treatment workflows was completed. In both end-to-end tests, a good

agreement between measurements and treatment planning system (TPS) calculations has highlighted the feasibility of adaptive treatment workflows in the presence of intra- and inter-fraction motion.

Induced by the magnetic field, the existence of hot and cold spots in the dose distribution around air bubbles is a specific problem in MRgRT. For this purpose, film dosimetry has been used to measure the dose distributions around air bubbles in a magnetic field. The agreement with calculations from clinical TPS gives confidence that in the situation when air pockets occur in the patients, MRgRT treatments can be delivered safely.

Since organ and target motion in radiotherapy in combination with treatment adaptation is a complex process, a simulator was developed to evaluate the impact of intra- and inter-fraction organ motion. This simulator allows to mimic several treatment scenarios and evaluate their residual uncertainties. It can be used for educational purposes.

A simulation test bed has been developed to calculate motion dependent UWB RADAR data. Based on a virtual phantom a dataset of 96 different 3D matrixes with phantom electromagnetic properties was established from 12 different cardiac and 8 different respiration phases. From this data set both UWB-RADAR and MR reference data sets was generated to exploiting respiratory and cardiac motion data available for various scenarios. For comparisons and uncertainty evaluations ground truth motion data can be extracted from the available virtual phantom models. For validation, a dynamically deformable phantom suitable for combined MR-UWB-RADAR measurements was constructed. This is first big step in the development of UWB RADAR as independent method to track organ motion with both, high spatial and high temporal resolutions in MRgRT. In addition a method to generate synthetic CT data from MR images was developed [17] Objective 4 was fully achieved.

Impact

The consortium has currently published 17 papers in peer-reviewed journals on an open access basis, 2 PhD thesis have been prepared and 1 MSc thesis. In addition, 85 scientific presentations on international congresses were given. The stakeholder committee consisted of 15 members from academic hospitals, medical industry and standards developing organisations. Alongside progress meetings, engagements with individual stakeholders were organised to discuss topics such as; response change of detectors in magnetic fields, machine QA of MRgRT facilities and benchmarking of Monte Carlo codes.

In June 2018, a successful satellite symposium was organised by the consortium on the topic of ‘Standards and procedures for dosimetry and QA in MRgRT’ with 120 attendees from 12 countries representing manufacturers, hospitals and standards developing organisations. In total, 14 presentations were given by consortium partners. The symposium covered various relevant topics (such as: reference Dosimetry for MRgRT devices, relative Dosimetry for MRgRT Treatment planning system, Monte Carlo simulations in magnetic field and QA and workflow procedures for MRgRT). In addition, the project organized several workshops such as for Monte Carlo simulations in the presence of magnetic fields, and the developed simulator.

Impact on industrial and other user communities

- hospitals and patients

The preliminary method for routine reference dosimetry at the MR-linac verified by water calorimetry in this project has been used in the clinical introduction of the MR-linac. In addition, this project has developed all elements required for a metrological infrastructure for reference dosimetry in MRgRT facilities. The preliminary method for routine reference dosimetry at the MR-linac verified by water calorimetry in this project has been used in the clinical introduction of the MR-linac. This method and other developed methods are available for clinics to assist them with reference dosimetry. Several consortium partners have assisted the commissioning of MRgRT facilities in UK, France, Germany, Denmark and Australia by performing reference dosimetry, which helped clinics in starting up the clinical treatments with MRgRT.

Clinical treatment with the MR-linac has started in May 2017 for the Unity MR-linac which is the first worldwide. Two other clinical partners started clinical MRgRT treatments afterwards. Apart from the described reference dosimetry method, several results of this project have been used in the preparation of clinical treatments, such as; methods for machine and patient QA (WP4) and characteristics of detectors used for the measurements of TPS input data (WP2). As such this project has accelerated the clinical acceptance procedures so that patients have access to a more advanced radiotherapy treatment on a shorter term. Given the interest in

MRgRT facilities many more hospitals will follow. The results disseminated from this project will have a strong contribution to the clinical introduction of MRgRT in the wider community of radiotherapy clinics.

- medical devices

One commercially available MRgRT facility has achieved CE mark in 2018. Approval was based on several results of this project. To date, orders for MRgRT facilities since CE mark is higher than 50 (including already installed facilities). Therefore, the commercial expectations for the next years are high.

The existing water phantom for measurements of dose profiles as input data for TPS, has been further optimised in this project. A company who is also stakeholder in this project has started the product development and the process for commercialisation, which is expected for 2020.

The laboratory facilities for the determination of the detector's characteristics and correction factors consisting of a linear accelerator and an electromagnet, which have been developed in this project will allow manufacturers of detector and measurement equipment to characterise and calibrate their own equipment. This means that they will have commercially available detectors characterised and calibrated under stable laboratory conditions and close to clinical situations, thereby improving confidence in their equipment. As such this project has enhanced the safe introduction of (new) medical devices and measurement equipment introduced in the field of MR-guided radiotherapy. Since many new developments of measurement and QA equipment for MRgRT are to be expected for the coming years it will enhance economic and commercial activities in this field for the longer term.

Impact on the metrological and scientific communities

This project discovered the importance of the dead volume in ion chambers for measurements in the presence of magnetic field. This new discovery has been the basis for more papers on this topic which attempted to investigate the consequences for reference dosimetry and which attempted to measure the size of this dead volume more accurate.

Several fundamental concepts describe the response behaviour of ionisation chambers of which the Bragg-Gray cavity theory is the most well-known. These concepts have been shown to be essential for both the metrological community and the medical physics community in the development of standards, reference dosimetry formalisms and detector development. The investigations in this project indicate that these concepts are inadequate to describe the response behaviour of ionisation chambers in the presence of magnetic fields. The data measured in this project, to describe the response behaviour of ionisation chambers as a function of energy and magnetic field strength and orientation (WP1, WP2) will provide new information and is essential to underpin fundamental dosimetrical concepts, for the description of detector response in the presence in magnetic fields, to be developed in the future.

Impact on relevant standards

A missing step is the development of a new code of practice for MRgRT. With several stakeholders (standards developing organisations (NCS, DIN, IPEM) and hospitals) the topic of reference dosimetry was discussed at the satellite symposium. The outcome of this discussion is that it is high preferable to develop the CoP as add-on to existing CoPs. The consortium has drafted a review paper on this topic which contains an evaluation of the existing literature on this topic (which is to a large extent output of this project) and of unpublished data from this project. This review paper will be the basis for future add-ons to CoPs.

In addition, several phantoms and dosimetry techniques for QA of facilities and patient treatment have been developed in this project. With the increasing use of MRgRT the demand for QA standards increases. The developed methods from this project described in the literature will give a significant contribution to these standards. This will in the end harmonise the treatment delivery in MRgRT.

The project has contributed to the report piloted by IRSN and SFPM 'Etude sur l'installation et la mise en œuvre d'accélérateurs linéaires couplés à un système d'imagerie par résonance magnétique en radiothérapie (IRMlinac)' (Rapport n° PSE-SANTE/2018-00007) which was drafted upon request of the ASN the France nuclear safety authority.

Longer-term economic, social and environmental impacts

After recent CE approval the number of installed and commissioned MRgRT facilities has increased rapidly. In addition, the number of new orders for these facilities remains high. The metrological basis for MRgRT dosimetry established in this project, which has also been used in the clinical introduction of MRgRT by the

early adopters, will be input for future standards and CoPs. This will help clinics and manufacturers in future with the commissioning of new facilities, and as such it contributes to enhanced economic activities in this field on the long term.

In addition, with the increase in hospitals using MRgRT the number of patients that benefit from this advanced treatment also increases. Their potential benefits are:

- Reduced number of treatment fractions because accurate imaging allows for hypofractionation
- Reduced dose because of improved treatment response monitoring by MRI
- And consequently, improved quality of life and treatment outcome

In addition, via clinical trials it will be investigated whether MRgRT is a treatment option for tumour sites for which to date no treatment exist, such as pancreas. In this context the results of this project potentially contribute to the QA of these trials.

List of publications

[1] Prez L De, Pooter J De, Jansen B, Woodings S, Wolthaus J. Commissioning of a water calorimeter as a primary standard for absorbed dose to water in magnetic fields Commissioning of a water calorimeter as a primary standard for absorbed dose to water in magnetic fields. Phys Med Biol 2019. https://doi.org/10.1088/1361-6560/aaf975

[2] de Prez L, Woodings S, de Pooter J, van Asselen B, Wolthaus J, Jansen B, et al. Direct measurement of ion chamber correction factors, k Q and k B , in a 7 MV MRI-linac . Phys Med Biol 2019;64:105025. https://doi.org/10.1088/1361-6560/ab1511

[3] Raaymakers BW, Jürgenliemk-Schulz IM, Bol GH, Glitzner M, Kotte ANTJTJ, van Asselen B, et al. First patients treated with a 1.5 T MRI-Linac: clinical proof of concept of a high-precision, high-field MRI guided radiotherapy treatment. Phys Med Biol 2017;62:L41–50. https://doi.org/10.1088/1361-6560/aa9517

[4] van Asselen B, Woodings SJ, Hackett SL, van Soest TL, Kok JGM, Raaymakers BW, et al. A formalism for reference dosimetry in photon beams in the presence of a magnetic field. Phys Med Biol 2018;63:125008. https://doi.org/10.1088/1361-6560/aac70e

[5] Pojtinger S, Dohm OS, Kapsch R-PP, Thorwarth D. Ionization chamber correction factors for MR-linacs. Phys Med Biol 2018;63:11NT03. https://doi.org/10.1088/1361-6560/aac4f2

[6] Woodings SJ, Asselen B Van, Soest TL Van. Technical Note : Consistency of PTW30013 and FC65-G ion chamber magnetic fi eld correction factors n.d. https://doi.org/10.1002/mp.13623

[7] Spindeldreier CK, Schrenk O, Bakenecker A, Kawrakow I, Burigo L, Karger CP, et al. Radiation dosimetry in magnetic fields with Farmer-type ionization chambers: Determination of magnetic field correction factors for different magnetic field strengths and field orientations. Phys Med Biol 2017;62:6708–28. https://doi.org/10.1088/1361-6560/aa7ae4

[8] Pojtinger S, Kapsch R-P, Dohm O, Thorwarth D. A finite element method for the determination of the relative response of ionization chambers in MR-linacs: simulation and experimental validation up to 1.5 T. Phys Med Biol 2019;accepted. https://doi.org/10.1088/1361-6560/ab2837

[9] Malkov VN, Hackett SL, Wolthaus JWH, Raaymakers BW, van Asselen B. Monte Carlo simulations of out-of-field surface doses due to the electron streaming effect in orthogonal magnetic fields. Phys Med Biol 2019;64:115029. https://doi.org/10.1088/1361-6560/ab0aa0

[10] Malkov VN, Hackett SL, van Asselen B, Raaymakers BW, Wolthaus JWH. Monte Carlo simulations of out-of-field skin dose due to spiralling contaminant electrons in a perpendicular magnetic field. Med Phys 2019;46:1467–77. https://doi.org/10.1002/mp.13392

[11] Billas I, Bouchard H, Oelfke U, Duane S. The effect of magnetic field strength on the response of Gafchromic EBT-3 film. Phys Med Biol 2019;64:06NT03. https://doi.org/10.1088/1361-6560/ab0503

[12] Mann P, Saito N, Lang C, Runz A, Johnen W, Witte M, et al. Validation of 4D dose calculation using

an independent motion monitoring by the calypso tracking system and 3D polymer gel dosimetry. J Phys Conf Ser 2017;847:012040. https://doi.org/10.1088/1742-6596/847/1/012040

[13] Mann P, Schwahofer A, Karger CP. Absolute dosimetry with polymer gels—a TLD reference system. Phys Med Biol 2019;64:045010. https://doi.org/10.1088/1361-6560/aafd41

[14] Elter A, Dorsch S, Mann P, Runz A, Johnen W, Karger CP. Compatibility of 3D printing materials and printing techniques with PAGAT gel dosimetry. Phys Med Biol 2019;64:04NT02. https://doi.org/10.1088/1361-6560/aafef0

[15] Dorsch S, Mann P, Lang C, Haering P, Runz A, Karger CP. Feasibility of polymer gel-based measurements of radiation isocenter accuracy in magnetic fields. Phys Med Biol 2018;63:aac228. https://doi.org/10.1088/1361-6560/aac228

[16] Dorsch S, Mann P, Elter A, Runz A, Klüter S, Karger CP. Polymer gel-based measurements of the isocenter accuracy in an MR-LINAC. J Phys Conf Ser 2019;1305:012007. https://doi.org/10.1088/1742-6596/1305/1/012007

[17] Kraus KM, Jäkel O, Niebuhr NI, Pfaffenberger A. Generation of synthetic CT data using patient specific daily MR image data and image registration. Phys Med Biol 2017;62:1358–77. https://doi.org/10.1088/1361-6560/aa5200

Project start date and duration:	01 June 2016, 36 months	
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Internal Funded Partners: 1 VSL, The Netherlands 2 CEA, France 3 NPL, United Kingdom 4 PTB, Germany	External Funded Partners: 5 DKFZ, Germany 6 UMC, The Netherlands 7 UoM, United Kingdom	Unfunded Partners: 8 Christie, United Kingdom 9 METAS, Switzerland
RMG: -		