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Improved Dosimetry Enables Online MRI-guided Radiotherapy

VSL, together with other NMI, DI and academic partners, has established trusted absolute dosimetry to enable online MRI-guided radiotherapy and enhance cancer patient treatment

The National Metrology Institute in The Netherlands (VSL), Coordinator Netherlands (NL)



The Challenge

Magnetic resonance imaging (MRI) guided radiotherapy (MRgRT), which combines high-resolution imaging with radiation therapy, has shown promise as an innovative non-invasive cancer treatment. However, existing methods for delivering accurate radiation doses were incompatible with a prototype MRgRT device, so-called MR-linacs. Without a measurement method compatible with the new technology to ensure delivery of accurate radiation doses, patient trials could not proceed.

In 2022, the number of new cancer diagnoses was estimated at 20 million, of which half of the patient's received radiotherapy in the course of their treatment.¹ Here radiotherapy, which is a non-invasive treatment, is used either as stand-alone treatment or in combination with more invasive treatments such as chemotherapy and surgery. In radiotherapy a harmful dose of invisible ionizing radiation is delivered to the tumour. Effective radiotherapy relies on delivering a radiation dose that is sufficient to destroy tumour cells while minimizing side effects, due to the unavoidable dose that is delivered to healthy tissue. To optimize this balance, it is important to see what you treat. Magnetic resonance imaging-guided radiotherapy, which integrates high-resolution Magnetic Resonance Imaging (MRI) with a radiotherapy device via a linear accelerator (Linac), or MR-linacs, developed in collaboration with the medical device industry and hospitals, fulfils this demand.

Critical to successful radiotherapy is the delivery of accurate radiation doses, with clinical evidence that the dose delivered to the patient must be within 2.5 %.² Prior to the clinical introduction of radiotherapy equipment, hospitals must calibrate the monitoring device of this equipment by measuring the radiation dose under reference conditions, using secondary standard ionization chambers. However, the existing methods for reference dosimetry, which safeguard the calibration chain from primary dosimetry standards at national metrology institutes to secondary standards and field standards used in clinical devices, could not work with MR-linacs as the presence of the MRI scanner magnetic fields would interact with treatment beams and ionization chambers. Without recognized methods to ensure accurate measurements of radiation doses, advancement to patient trials and, eventually, clinical treatments could not be given the go-ahead.

¹ Zhu H, et al. Global radiotherapy demands and corresponding radiotherapy-professional workforce requirements in 2022 and predicted to 2050: a population-based study. *The Lancet Global Health*, 2024; 12, e1945-e1953

² International Commission on Radiation Units and Measurements (ICRU) 1976, Determination of Absorbed Dose in a Patient Irradiated by Beams of X or Gamma Rays in Radiotherapy Procedures. ICRU Report 24, Bethesda, Maryland and Washington DC.

The Solution

In the EMRP project MRI Safety,³ VSL showed the potential of a newly designed portable water calorimeter as a primary standard for absorbed dose measurements in the presence of magnetic fields. In the context of the EMPIR project Metrology for MR guided radiotherapy,⁴ VSL optimized the water calorimeter to serve as a primary standard for the prototype MR-linac. The calorimeter was characterized, tested, and used for the first time worldwide for the measurement of radiation dose in an Elekta Unity MR-linac at UMCU, with and without a magnetic field present. By comparison with the optimized calorimeter, calibration coefficients for several secondary standard ionization chambers were determined. Based on this dataset, device-specific correction factors to account for the presence of magnetic fields were determined for secondary standard ionization chambers commonly used by clinicians for reference dosimetry.

A method to deliver reference dosimetry in MRI-linacs was devised by applying these correction factors to existing methods, enabling clinicians to calibrate their MRI-linac's beams based on secondary standard ionization chambers, as is more commonly used in practice.

Two other methods to determine device-specific correction factors were devised, accounting for magnetic field orientation and the beam axis. The first method, developed by PTB, uses Monte Carlo simulations coupled with finite element modelling. The second method developed by NPL uses measurements with solid-state dosimeters. Both methods showed good consistency with the water calorimeter-measured correction factors. The resulting methods and datasets for the correction factor have been evaluated in a review paper.⁵ This has served as the basis for two protocols for reference dosimetry in MRI-linacs.^{6,7}

A Quantifiable Impact

Ionization chambers calibrated to the optimized primary standard were used to deliver the first clinical treatments with an MR-linac, an Elekta Unity at UMCU, in the First in Man study,⁸ supported by the Dutch Cancer Society. Four spine cancer patients were treated from May to July 2017. Absolute doses post-treatment were established as highly accurate, no adverse events were reported by November 2017, and palliative effects were achieved in all treated patients, demonstrating the clinical feasibility of MRgRT. The results of the research enabled clinical trials using the prototype MR-linac device to proceed, while enabling metrology

³ EMRP Project HLT06 MRI safety, "Metrology for next-generation safety standards and equipment in MRI"
<https://www.euramet.org/research-innovation/search-research-projects/details/project/metrology-for-next-generation-safety-standards-and-equipment-in-mri>

⁴ EMPIR Project 15HLT08 MRgRT, "Metrology for MR guided radiotherapy"
<https://www.euramet.org/casestudies/casestudiesdetails/news/absolute-dosimetry-for-mr-linacs>

⁵ de Poeter, J et al. 2021 Phys. Med. Biol. 66 05TR02 DOI 10.1088/1361-6560/ab9efe

⁶ AAPM task group report 351: Protocol for clinical reference dosimetry in external beam MR-guided radiotherapy.
<https://doi.org/10.1002/mp.17884>

⁷ Billas, I et al. 2025. Reference dosimetry for MRI-Linacs: an addendum to the 2020 IPEM code of practice for high-energy photon therapy dosimetry. Phys. Med. Biol. 70 085007. DOI 10.1088/1361-6560/adc0e0

⁸ Raaymakers, BW et al. 2017 Phys. Med. Biol. 62 L41 DOI 10.1088/1361-6560/aa9517

institutes to use the results to type-test ionization chambers and deliver proficiency testing (PT) services.

The Elekta Unity gained its CE mark in June 2018, providing clearance for commercial sales and clinical use across Europe. With approval from the U.S. Food and Drug Administration (FDA) and China's National Medical Products Administration (NMPA), regulatory clearance was subsequently extended to over 75 countries. To date, more than 240 MRI linacs have been installed worldwide, representing an annual treatment capacity of 48 000 patients.

Since the CE mark was granted, several clinical trials have demonstrated the benefit of MRgRT. For prostate cancer, positive effects from MRgRT on treatment outcome have been reported.^{9,10} For selected patient groups with renal cancer, the effectiveness of MRgRT was demonstrated to be on the same level as invasive treatments, thereby offering a non-invasive alternative to invasive treatments such as surgery.¹¹ In addition, MRgRT has been used to reduce treatment time from 30 fractions of 10 minutes to 2 fractions of 45 minutes,^{12,13} representing a significant economic improvement.

International Basic Safety Standards¹⁴ serve as the basis for national legislation regarding medical exposures to ionizing radiation. These standards require that all sources giving rise to medical exposure be calibrated to appropriate quantities using internationally or nationally accepted protocols, and that calibration of all dosimeters used for patient dosimetry and for source calibration be metrologically traceable to a standards dosimetry laboratory. The developed primary standards, characterized secondary standards, data sets of correction factors, and methods for clinical dosimetry are the basis for demonstrating compliance with these regulations.

The establishment of reliable absolute dose measurements advanced the development of MRgRT and clinical acceptance of MR linacs, enabling hospitals to deploy this advanced form of radiotherapy. This trusted absolute dosimetry and superior imaging technique has resulted in more precise, personalized cancer treatment and potentially improved quality of life.

⁹ Kishan AU, et al. Magnetic Resonance Imaging Versus Computed Tomography Guidance for Stereotactic Body Radiotherapy in Prostate Cancer: 2-year Outcomes from the MIRAGE Randomized Clinical Trial. *Eur Urol.* 2025 Jun; 87(6):622-625. DOI: 10.1016/j.eururo.2024.10.026

¹⁰ Hall, WA et al. Daily Online Adaptive Recontouring for Prostate Cancer Using 1.5 Tesla Magnetic Resonance Image Guidance (MRgRT) Improves Patient Reported Urinary Symptoms, A Prospective, International, Observational Cohort Study (NCT04075305), *International Journal of Radiation Oncology Biology Physics*, Volume 123, Issue 1, Supplement, 2025, Pages S81-S82. <https://doi.org/10.1016/j.ijrobp.2025.06.1104>

¹¹ Siva S, et al. Ultra-hypofractionated stereotactic ablative body radiotherapy for primary renal cell carcinoma: 5-year outcomes from a pooled analysis of the FASTER trials. *Lancet Oncol.* 2026 Jun; 27(6):721-728. DOI: 10.1016/S1470-2045(26)00170-1

¹² Lalmahomed TA, et al. Two-fraction Ultrahypofractionated Radiotherapy with focal B0ost for intermediate-risk, localized prostate cancer (TURBO): study protocol of a phase II, randomized controlled clinical trial. *Trials.* 2025 Dec 29;26(1):586. DOI: 10.1186/s13063-025-09297-5.

¹³ Cooper S, et al. HERMES: Randomized Trial of 2-Fraction or 5-Fraction Magnetic Resonance Imaging-Guided Adaptive Prostate Radiation Therapy. *Int J Radiat Oncol Biol Phys.* 2025 Nov 1;123(3):773-782. DOI: 10.1016/j.ijrobp.2025.05.008

¹⁴ Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards. 2014. <https://doi.org/10.61092/iaea.u2pu-60vm>

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A complete list of participants is provided on the EMPIR Project 15HLT08 MRgRT page.¹⁵

POC: Jacco de Pooter, JdPooter@vsl.nl

¹⁵ EMPIR Project 15HLT08 MRgRT, “Metrology for MR guided radiotherapy”
<https://www.euramet.org/casestudies/casestudiesdetails/news/absolute-dosimetry-for-mr-linacs>