Online MR image-guided radiotherapy: MR-linac

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Introduction

The concept of combining magnetic resonance imaging (MRI) technology with a linear accelerator (linac) was first realised in the early 2000s. The subsequent development of the MR-linac has enabled online MR image-guided radiotherapy (MRgRT) and thus online adaptive radiotherapy. Currently there are two clinical systems available with two more in development phase (table 1). The MRIdian system (ViewRay), consisting of a 0.35T MRI scanner combined with a three head Cobalt 60 radiation source, was first to treat a patient in 2014. In 2017, the first patient was treated on the MRIdian MR-linac (6MV) and in 2018 the first patient was treated (spinal metastases) on the Elekta clinical system, the Unity MR-linac at UMCU (Utrecht).

The installation of an MR-linac at The Royal Marsden NHS Foundation Trust was made possible by a £10m grant from the Medical Research Council to the Institute of Cancer Research (ICR), with additional support from The Royal Marsden Cancer Charity. Introducing MR into the radiotherapy department had implications on safety and required staff training, both of which are described in further detail below. Initial experiences with imaging and treating patients are also presented.

MRI in the radiotherapy department

Installing an MR machine in the radiotherapy department required close collaboration with diagnostic colleagues who advised on safety and staff training. Bespoke local rules were developed that combined the Ionising Radiation (Medical Exposure) Regulations (IR(ME)R, 2017), the Medicines and Healthcare Products Regulatory Agency (MHRA, 2015) and the American College of Radiology (ACR, 2013) guidelines. It was also ensured that the local rules were similar to the existing local rules of the diagnostic MRI department. The MR-linac suite was divided into four zones based on the ACR guidelines (figure 1). A complex system of authorisation and access was developed. MR-linac staff were trained and authorised in accordance with their role. An overview of general safety training was delivered to all other staff in radiotherapy department.

Elekta Unity MR-linac

The MR-linac combines a 7MV linac with a 1.5T magnet and the design of the system enables an ultra low field magnetic zone at the location of the electron gun and the waveguide to enable the photon beam production. The main challenge in all MR-linac systems is how to minimise the magnetic and radiofrequency (RF) interference between the magnet and the accelerator. On the MR-linac, the accelerator is positioned outside of the Faraday cage in order to manage the RF interferences between the linac and the MRI scanner. The proof of concept of this approach was first demonstrated using a prototype system.

Imaging

The MR-linac was provided with protocols for each anatomical region: brain, head and neck, thorax, abdomen and pelvis. Acquisition times vary between two minutes (pelvis) and six minutes (pelvis, large field of view) (figure 2). Navigated sequences are also available for motion artefact reduction in the thorax and abdomen.

At The Royal Marsden NHS Foundation Trust, images have been acquired on healthy and patient volunteers under the PRIMER (Development of Daily Online Magnetic Resonance Imaging for Magnetic Resonance Image Guided Radiotherapy) study, which aims to investigate image quality of Elekta-provided or research-developed sequences to enable contouring and adaptive replanning.

Functional imaging and diffusion weighted imaging (DWI) are under development to assess tumour response during treatment.

<table>
<thead>
<tr>
<th>System (manufacturer)</th>
<th>Beam energy (MV)</th>
<th>Field strength (Tesla)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRIdian (ViewRay)</td>
<td>Cobalt or 6MV</td>
<td>0.35T</td>
</tr>
<tr>
<td>Unity (Elekta)</td>
<td>7MV</td>
<td>1.5T</td>
</tr>
<tr>
<td>Aurora-RT (MagnetTx)</td>
<td>6MV</td>
<td>0.5T</td>
</tr>
<tr>
<td>Australian</td>
<td>6MV</td>
<td>1.0T</td>
</tr>
</tbody>
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TABLE 1: MR radiotherapy systems; clinical and in development (italics).
Treatment

Patients were consented to the PRISM (Prostate Radiotherapy Integrated with Simultaneous MRI) study for radical radiotherapy to the prostate (60Gy in 20 fractions). The primary endpoint of the trial is feasibility of treatment delivery on MR-linac.

Quality assurance (QA) and workflow procedures were established, which were reflective of existing departmental procedures. The QA of the linac followed IPEM81 guidance where possible. Due to the unique geometry of the machine and the interaction of the secondary electron with the magnetic field a series of additional tests were developed in collaboration with the Elekta MR-linac research consortium. The National Physics Laboratory (NPL) provided support for the absolute calibration of the linac and a peer review of the established procedures was carried out before the start of the first patient treatment.

Pre-treatment: currently the pre-treatment workflow follows the standard departmental protocol for prostate radiotherapy. Planning images are acquired on a conventional CT scanner with an overlay in place to replicate the MR-linac couch. A diagnostic MRI is also acquired on the same day with the patient positioned using radiotherapy immobilisation and on a flat tabletop. Contouring of targets and organs at risk is informed using a fusion of the planning CT and MRI images. A reference plan is created using the Monaco (version 5.4, Elekta AB, Stockholm, Sweden) treatment planning system and consists of seven field step and shoot intensity modulated radiotherapy beams. Pre-treatment verification of the reference plan was performed using an MR compatible version of the PTW Octavius 4D system. A back-up plan for a conventional linac is also created in the event treatment is not feasible on MR-linac.

Treatment workflow: prior to treating the first patient, the MR-linac specific workflow was practised and streamlined while imaging patients under the PRIMER study (up to the point of treatment). The online adaptive workflow includes making a judgement, either prior to treating or following imaging acquisition, regarding whether to adapt or not. If adapting, then further consideration is required regarding how much of, and which, anatomical structures to recontour. The treatment plan is then optimised and recalculated. The new plan is mostly automatically checked using an in-house tool and an independent dose calculation engine. After plan approval further imaging is carried out to verify the patient’s position immediately prior to treatment delivery. During treatment, real-time 2D images are acquired in the sagittal, coronal and axial planes. To date, observed inter-fraction changes in patient anatomy have ranged from minimal to gross changes (figure 3). Additional images for research purposes can be acquired while the plan is being optimised and post treatment.

The MR images acquired and plans created will be analysed offline to further inform practice. Recruitment will be increased to include additional tumour sites such as rectum and bladder in the near future.

Conclusion

The clinical implementation of the MR-linac has been successful. Images have been acquired on more than 65 patient and healthy volunteers and five patients have received radiotherapy for prostate cancer. As each patient has a daily plan adapted to their daily anatomy, over 100 unique treatments have been planned and delivered. The benefit and potential of MR-linac treatments will continue to be investigated.

Acknowledgements

We acknowledge NHS funding to the NIHR Biomedical Research Centre at The Royal Marsden and The Institute of Cancer Research. Research at The Institute of Cancer Research is also supported by Cancer Research UK under Programme C39589/A19727. ICR/BMH is a member of the Elekta MR-linac research consortium.

References