MRI in Radiotherapy Planning: Our Experience so far

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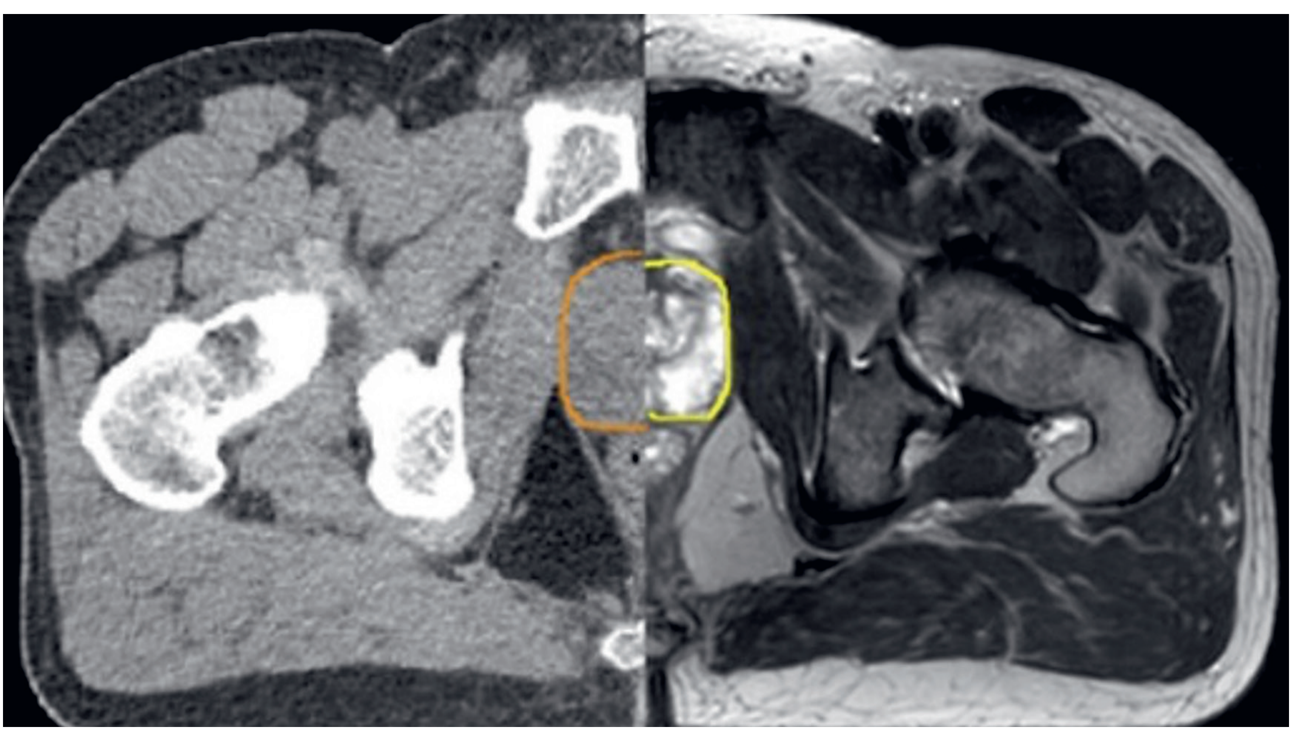
Background

Advances in radiotherapy have made tumor definition increasingly important. There is extensive literature on the advantages of using magnetic resonance imaging (MRI) for tumor-volume and organ-at-risk delineation compared to computed tomography (CT) alone, with patients potentially receiving more accurate treatment at higher doses and with fewer side effects. Yet despite the many advantages, introducing MRI into the radiotherapy planning pathway is a challenge and far from standard practice in the UK and Ireland.

The Radiotherapy Department at the North West Cancer Centre in Altnagelvin, Northern Ireland, is a new facility equipped with state-of-the-art equipment capable of delivering some of the most technologically advanced radiotherapy treatment regimens currently in use anywhere in the world. However, although the treatment regimens can be delivered, accuracy and efficacy depend on precisely locating and defining the treatment-planning target volumes. Current treatment-planning technology dictates that CT imaging is the essential standard, as electron-density values derived from the scans are required for accurate dose calculation. However, CT imaging is not the modality of choice for visualizing soft tissue.

The advancement of treatment technologies has enabled more precise delivery of radiation to the target volume. This may permit reducing the volume of irradiated tissue but with these reduced volumes, the risk of a geographical miss increases and consequently there is a greater need for improved imaging for better visualization of tumour and organs at risk (OARs). With its superior



soft-tissue visualization capabilities (Fig. 1), wide range of image contrasts, and the availability of numerous functional imaging techniques, MRI has become a powerful tool for helping to accurately delineate treatment-planning target volumes.

MRI was introduced into the radiotherapy-planning pathway in September 2017. A multidisciplinary team of diagnostic and therapeutic radiographers, treatment planners, medical physicists, and clinicians was convened to establish this service, and close collaboration and cross-disciplinary training between all members of the team was vitally important for its successful implementation. Planning MRI was carried out in the days immediately following conventional CT simulation. All patients underwent identical preparation prior to both CT and MRI scans. They were immobilized in the treatment position using MR-compatible equipment. T2 SE axial and sagittal images were acquired (1.5T MAGNETOM Aera with software version *syngo* MR E11, Siemens Healthcare, Erlangen, Germany), imported into the Eclipse planning system (V15.5, Varian Medical Systems Inc., Palo Alto, CA, USA), and registered to the planning CT for volume delineation.

The service was initially offered to all patients for radical radiotherapy to the prostate at the North West Cancer Centre. The service was expanded in August 2018 to include patients for radical radiotherapy to the head and neck. As of December 2020, over 667 patients have been successfully scanned. Treatment review has shown that these patients have tolerated their radiotherapy well, with minimum side effects.

In this article, we describe some of our experience so far, and highlight the benefits of introducing MRI into the radiotherapy-planning pathway.

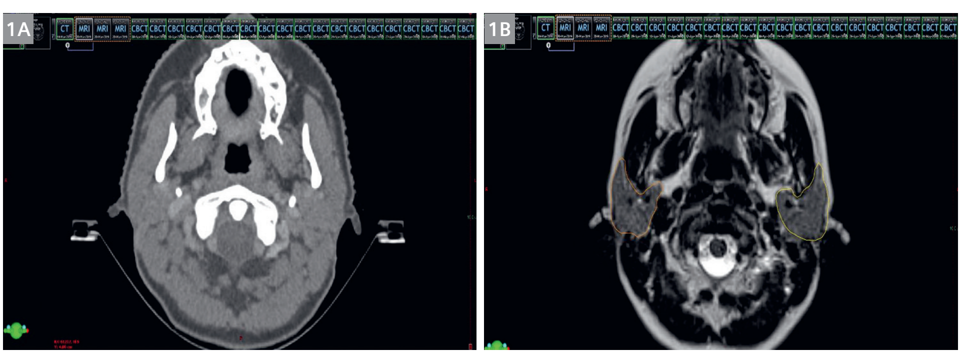
Treatment planning

To understand the benefits of introducing MRI into the radiotherapy-planning pathway, it is useful to understand the principles of target-volume delineation. In essence, we deliver a treatment to a volume much larger than the visible tumor itself. This is to account for multiple uncertainties and to avoid missing the tumor during daily radiotherapy treatments.

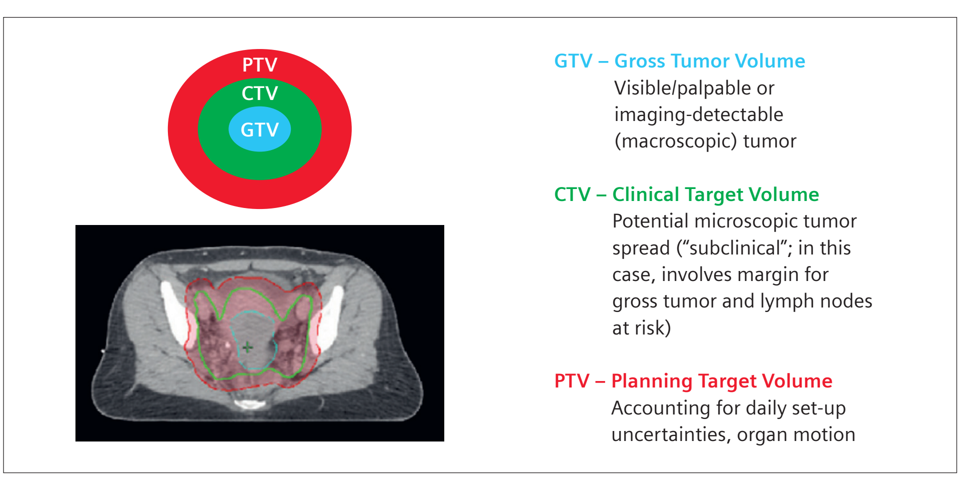
The geometric concepts of gross tumor volume (GTV), clinical target volume (CTV), and planning target volume (PTV) form the basis of modern radiotherapy planning.

The GTV refers to the position and extent of the gross tumor, i.e., what can be seen, palpated, or imaged.

The CTV contains the GTV, plus a margin for subclinical disease spread that cannot be fully visualized. The CTV is important because it must be adequately treated to achieve cure.



1 Superior soft-tissue contrast seen on MRI **(1B)** compared to CT scan **(1A)**.



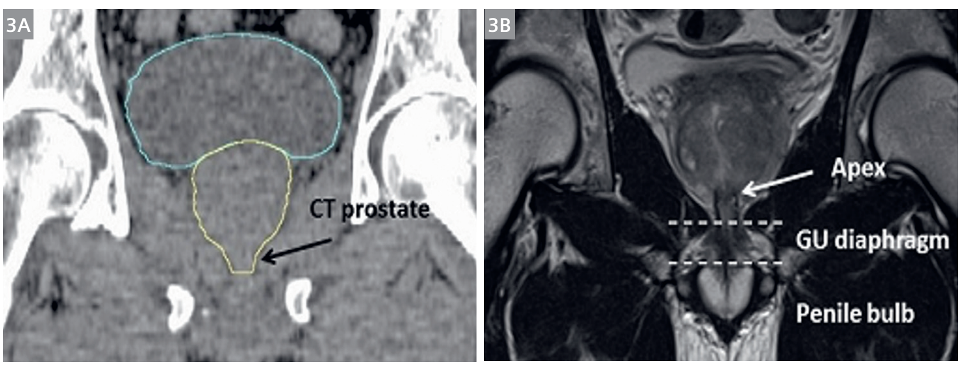
2 Radiotherapy target volumes.

The PTV allows for uncertainties in planning or treatment delivery. It is a geometric concept designed to ensure that the radiotherapy dose is actually delivered to the CTV.

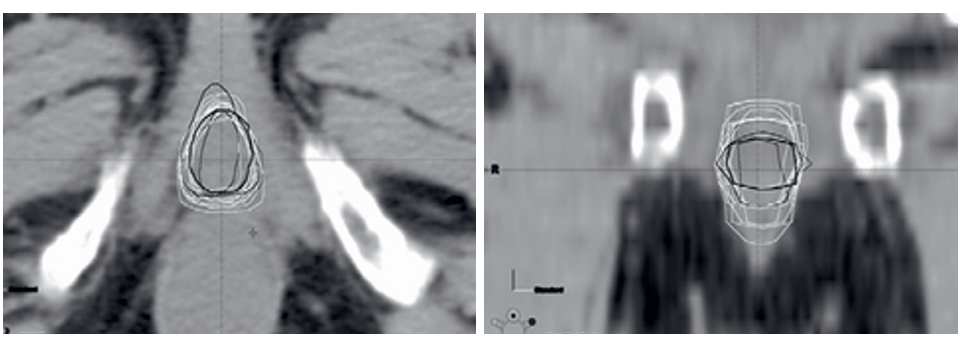
Radiotherapy planning must always consider critical normal tissue structures, known as organs at risk (OARs). An example of an OAR is the spinal cord, where damage to a small amount of normal tissue would be potentially life-threatening or life-changing.

Accurate delineation of these volumes using CT alone can be problematic. Determining tissue interfaces when delineating OARs such as the penile bulb and genitourinary (GU) diaphragm can be difficult using CT alone (Fig. 3), and the inferior image contrast often means that the same volume can be defined very differently by different users (Fig. 4). This has been shown to often lead to the GTV being defined larger than the true volume. Our experience is that prostate volumes defined using MRI fusion can be up to 30% smaller than those defined using CT alone, which in turn can affect the degree of genitourinary and gastrointestinal toxicity.

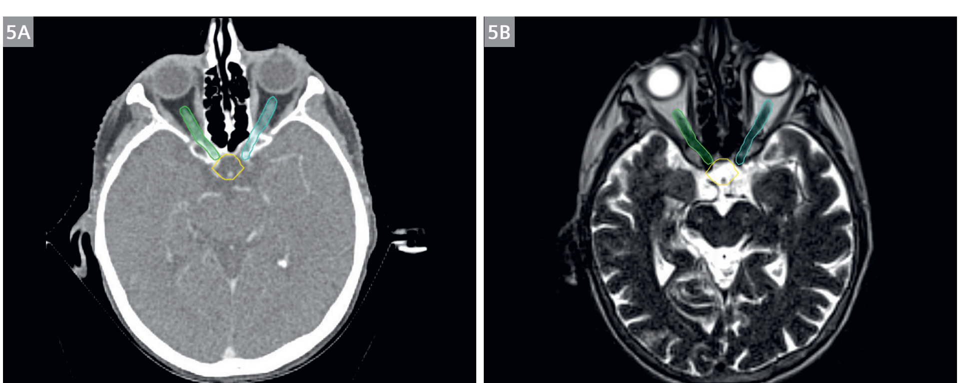
For head and neck cancers, precise delineation of intracranial OARs is crucial for accurate dose calculation, as radiotherapy can lead to visual or auditory deficits along with hormonal impairment or neurocognitive changes. Using CT imaging alone means that important normal structures are not always easily discernible. One area in which we have found MRI very useful is when delineating the optic chiasm (Fig. 5). The optic chiasm has a lower radiation tolerance than the surrounding cranial nerves, and over-irradiation of this structure can result in radiation-induced optic neuropathy. MRI has given our clinicians increased confidence in the accuracy of their delineation of this structure and other OARs within this region.



3 CT **(3A)** vs. MRI **(3B)** when delineating the penile bulb and GU diaphragm.



4 Inter User Variability. Images showing variability between users when defining planning volumes with CT alone.



5 Optic nerves (blue and green) and optic chiasm (yellow) on CT **(5A)** and MRI **(5B)**. *Reproduced with permission from [1].*

MRI allows us to acquire our planning images in multiple planes. Sagittal and coronal images are particularly useful when defining the superior and inferior extent of the GTV, and although CT allows us to retrospectively reconstruct sagittal and coronal images, they are of inferior quality when compared to MRI, as you can see from the sample images below (Fig. 6).

Another area in which MRI has proven very useful is when planning patients with prostheses[1]. Metal artifacts can often obscure the region of interest on a CT planning scan, even after the use of iterative metal artifact reduction (iMAR) algorithms (Fig. 7).

MRI sees the prostheses as a void, but importantly it allows us to visualize all the central structures clearly. Co-registering the MRI image against the planning CT image enables clinicians to accurately determine the volume of all relevant structures with increased confidence.

Pre-treatment imaging

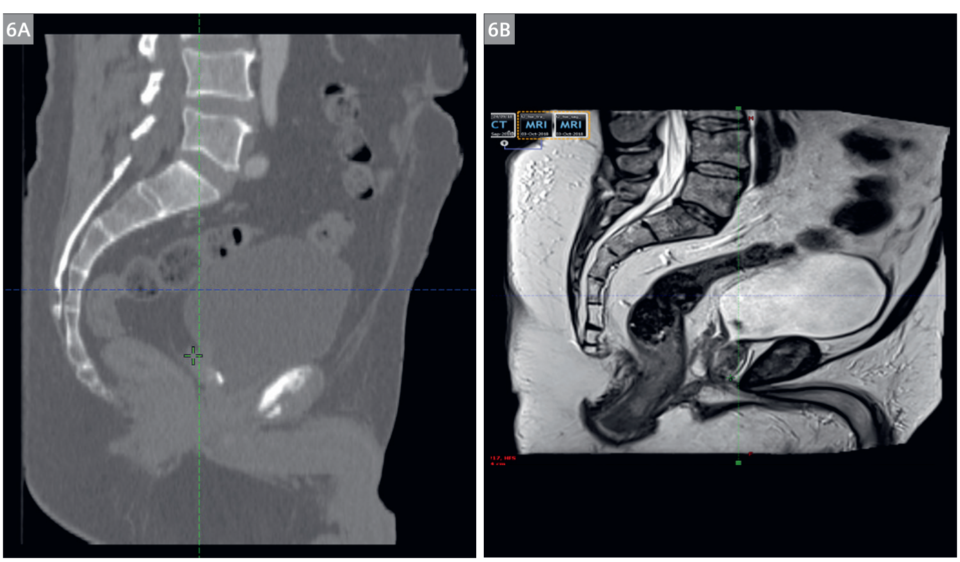
It is important that both, the CT and MRI planning images are acquired in the same reproducible position to minimize any problems with image registration and geometric distortion.

Our 1.5T MAGNETOM Aera scanner was purchased primarily for diagnostics. However, its wide (70 cm) short bore, large field of view (FOV), and uniformity in the static magnetic field (B_0) for minimizing geometric distortion allow us to accommodate the auxiliary RT positioning equipment and adapted MR coil positioning required to reproduce almost any radiotherapy treatment position – including arms above head within the bore – and achieve excellent image quality.

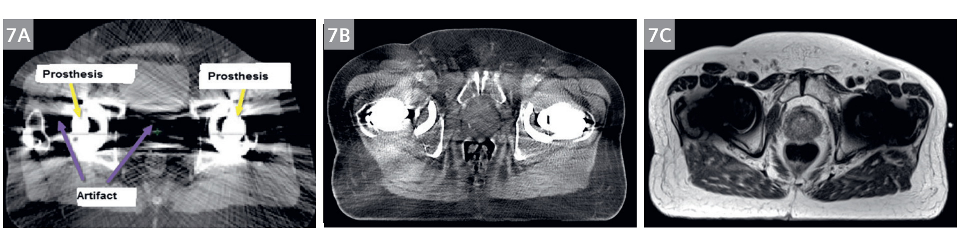
As MRI radiotherapy planning is becoming more common, the main manufacturers of MRI and radiotherapy equipment have responded to the demands of radiotherapy users and now provide auxiliary, MR-conditional equipment to enable most examinations to take place in the treatment position. A flat table top is required if we are to reproduce the CTSim positioning. We use an MRI-conditional, indexed flat table top that allows us to place all our immobilization devices in exactly the same position as for the CT scanner, which helps ensure accurate image registration (Figs. 8, 9).

The inclusion of RT-specific immobilization equipment – such as knee and ankle immobilization, indexing bars, wing boards, thermoplastic masks, and vacuum bags – is also necessary if we wish to exactly

[1]The MRI restrictions (if any) of the metal implant must be considered prior to patient undergoing MRI exam. MR imaging of patients with metallic implants brings specific risks. However, certain implants are approved by the governing regulatory bodies to be MR conditionally safe. For such implants, the previously mentioned warning may not be applicable. Please contact the implant manufacturer for the specific conditional information. The conditions for MR safety are the responsibility of the implant manufacturer, not of Siemens Healthineers.



6 Sagittal MPR from CT **(6A)** compared with sagittal MRI **(6B)**.

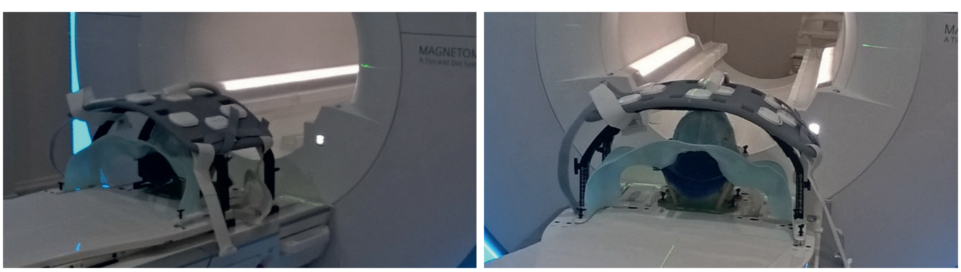


7 Hip prostheses on CT, pre- **(7A)** and post- **(7B)** iMAR, and on MRI[1] **(7C)**.

replicate the patient's treatment position. It is imperative that MR-conditional RT equipment is sourced and appropriately labelled before use. Scanning patients in the radiotherapy treatment position and the need for larger FOV coverage often mean that diagnostic coils cannot be used, as they are not designed to fit around RT positioning aids. Flexible surface coils in combination with coil bridges have to be used instead. Coil bridges prevent the surface coil from touching and distorting the patient's skin surface, and adjusting the bridge height ensures coil proximity to the patient.

Radiotherapy treatment positions are reproduced by using tattoos on the patient's skin and a laser positioning system. Standard positioning lasers on the MRI scanner are primarily used to center the patient to the magnet isocenter for optimal imaging, but they are not suitable for RT purposes. An RT-specific laser system (Fig. 10) is required to help align the patient according to their treatment tattoos when positioning for MRI scans.

8 An example of a prostate set-up for MR treatment planning, showing immobilization, coil supports, and coil positioning.



9 An example of a head-and-neck set-up for MR treatment planning, showing immobilization, coil supports, and coil positioning.

10 External laser bridge for MR treatment planning.

The RT laser is used to set-up the patient, whereas the MRI bore lasers are used to define the isocenter of the imaging volume. This ensures that the same position is replicated in both CT and MRI, aids in the image fusion of the two scans, and is supported by the addition of an RT Dot Engine software package.

Sequence requirements

Imaging requirements for therapy planning are different to those for diagnostic imaging, with the emphasis being placed on reducing geometric distortion as much as possible. Geometric inaccuracies caused by different patient positioning and the magnetic-field distortions inherent to MR images can significantly affect treatment doses to the patient as a result of inaccurate volume delineation if not minimized or corrected for. We can mitigate some of the factors that cause geometric distortions by, for example, ensuring the MRI scan is undertaken in the radiotherapy treatment position. However, other things need to be considered, too, such as choice of sequences and coil arrangements to maintain the balance between accuracy, patient comfort, and image quality.

Staffing and training

Integrating MRI planning into the pathway is very much a multi-disciplinary team effort, and the contribution from our medical physicists, dosimetrists, and clinicians has been invaluable.

Traditionally, the role of diagnostic radiographers has been limited to a diagnostic setting, where they are responsible for optimizing imaging for diagnosis. In contrast, the role of therapeutic radiographers is in the planning and treatment of patients once a diagnosis has been made. These roles would rarely ever overlap, but we have drawn many parallels between implementing MRI and when we first started using CT in radiotherapy.

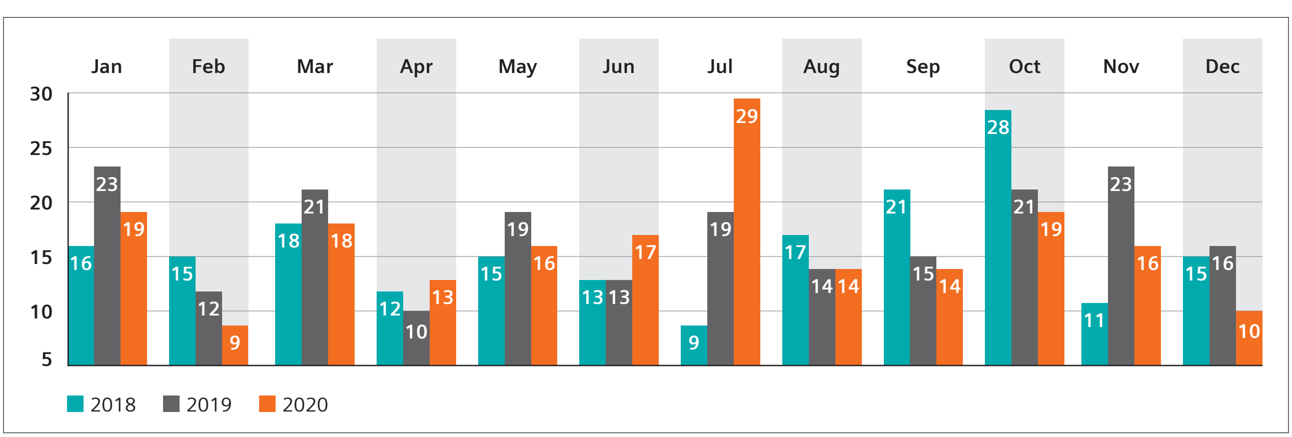
The first lesson we learned was to make friends with the MRI radiographers, as they were the people we interacted with the most and the people who could answer our questions (of which there were many!).

Successful integration requires radiographers to have a better understanding of both the RT and diagnostic work processes. Diagnostic MR radiographers have had to adapt to using different coil positioning and imaging techniques. In the future, therefore, we would like the diagnostic team to rotate into CT simulation so that they can gain an understanding of basic and advanced treatment set-ups to ensure these can be accurately replicated in the MRI scanner. The radiographers should also receive training in CT-MR image registration and volume delineation so that they can appreciate how the MR images are utilized, allowing for greater optimization of imaging parameters to better suit the requirements for radiotherapy treatment planning.

As a therapy team, we are currently responsible for patient preparation and positioning, but we do not currently acquire the MR planning images. We have undergone some local training to gain a better understanding of the basics of MRI and MR safety. However, to develop our role further, we are looking to complete more comprehensive training organized by academic institutions or vendors after the pandemic, followed by in-house competency training that will allow us to perform the planning scans under the supervision of the lead MR radiographer.

Patients scanned as of December 2020

By the beginning of December 2020, we had successfully scanned 667 patients in the CT/MRI fusion-planning pathway. Of these, 512 were prostate cancer patients, 145 were head and neck cancer patients, and 10 were rectal cancer patients who were scanned as part of a local study.



11 Patients scanned as of December 2020.

Treatment and post-treatment toxicity scoring is carried out routinely for all patients as part of their on-treatment review and post-treatment follow-up. A recent sample of 30 prostate patients showed that just under 80% reported toxicities graded 0 on the NCI CTC toxicity scoring scale (version 2.0, with RTOG), and less than 1% reported toxicities graded 3.

Conclusion

The use of MRI for radiotherapy planning is part of our evolving image-guided radiotherapy strategy, and local studies are planned to assess its impact so far with a view to reducing planning margins and associated toxicities in the near future. In the long term, clinicians have expressed an interest in functional imaging for tumor boosts, and for using MRI to plan stereotactic ablative radiotherapy (SABR) and adaptive treatments.

This truly collaborative service has had a positive impact on our staff and patients, examples of which include

- cross-disciplinary training resulting in upskilling, enhanced skills and knowledge, and evolving roles for staff;
- the introduction of new technologies into routine clinical practice, offering our patients access to the most up-to-date, effective treatments;
- improved inter-professional communication, facilitating better working relationships and environments, which impacts directly on patient care and experience.

The close collaboration between all members of the multi-disciplinary team with their differing skill sets has helped overcome a number of challenges and has provided a gateway for improved clinical outcomes and further research.

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