10 Years of Clinical Experience of MRI in Radiotherapy Treatment Planning: The Newcastle upon Tyne Story

Hazel McCallum, Ph.D.; Jonathan Wyatt, M.Sc.; Stephen Hedley, M.Sc.; Serena West, B.Sc.; Tim Dowling, B.Sc.; John Frew, F.R.C.R.; Rachel Pearson, F.R.C.R., Ph.D.; Christopher Walker, B.Sc

Northern Centre for Cancer Care, Newcastle upon Tyne Hospitals NHS Foundation Trust, Newcastle upon Tyne, UK

Introduction

The Northern Centre for Cancer Care installed its first MRI scanner dedicated for radiotherapy and oncology purposes in 2009, one of the first in the UK. Now with the hindsight of nearly ten years' experience, the evolution and development of MRI in radiotherapy planning in Newcastle upon Tyne will be described, from the first prostate patients planned with an MRI fused with a CT, extending to other treatment sites, to the first UK prostate patient to be treated with an MR-only pathway. In 2009, MRI was introduced as an important addition to the conventional CT planning process; it now forms an indispensable part of the radiotherapy service and paves the way for MR guided radiotherapy treatments with the introduction of MR-linacs.

Setting up the service

In 2007-08, when the hospital produced the specification for tender, there was only one wide-bore MRI scanner on the UK market, the Siemens MAGNETOM Espree 1.5T. An evaluation visit to Umea University Hospital, Sweden was a key influence, as the Newcastle team were able to observe an MRI scanner set-up for radiotherapy treatment planning, complete with laser bridge and in-house manufactured flat couch-top. Encouraged by the Umea University team, the purchase of a Siemens MAGNETOM 1.5T was confirmed in September 2008.

Multi-disciplinary collaboration was essential to the successful introduction of the service. Advice and guidance was provided by the Radiology Department throughout the planning, procurement installation and implementation stages. The appointment of an experienced MRI diagnostic radiographer was key, as their experience of sequence development as well as patient and staff safety provided some security in the early implementation phases.

Technical preparation

Commissioning for radiotherapy treatment planning

In 2009, there was little published data on performance standards for an MRI scanner for radiotherapy purposes. The radiotherapy department had access to a set of MagNet MRI QC phantoms, no longer commercially available and a large field of view geometric distortion phantom designed and built in Newcastle University [1].

An Evaluation Report on the Siemens MAGNETOM Espree, published by the NHS Purchasing and Supply Agency was used for much of the QC development and initial performance tolerances. Extensive experience of commissioning CT scanners and treatment imaging modalities was relied upon to develop additional tests which would consider radiotherapy aspects such as detailed geometric accuracy testing.

MRI commissioning tests

- Laser positional accuracy
- Couch level and scaling
- MRI compatibility of Immobilization devices
- Image quality
- Large FOV geometric distortion
- Geometric slice position and width
- Data transfer inter-operability
- Image fusion accuracy

MRI RT planning specific equipment

At the inception of our clinical service, there was no commercially available compatible flat couch top. We entered into a research collaboration with MediBord, Nottingham, UK to develop a bespoke flat couch top to fit with our scanner model and our preferred patient set-up. The couch top material is glass fibre which means the couch top is extremely light, at less than 4 kg, and easy to maneuver. This is particularly important when the radiotherapy couch top needs to be replaced by the diagnostic couch top for clinical trials patient scanning or diagnostic scans for radiotherapy patients. The couch-top securing mechanism was designed to fit into the coil strap fittings on the Siemens MAGNETOM couch. The flat couch top was designed by NCCC staff and manufactured by Medibord. Figure 1 shows details of the couch top.

When acquiring diagnostic MR images, typically the surface coils are directly wrapped around the patient. This can compress the patient's skin, which is not appropriate for radiotherapy planning where an accurate image of the patient's external contour is essential.

To avoid any distortion of the patient skin contour, coil supports for pelvis and head and neck were designed and manufactured in-house by the Mechanical Workshop, Northern Medical Physics and Clinical Engineering. The pelvis coil support secures in position in the coil strap fittings, is manufactured from polyethylene terephthalate glycol (PTEG) and polyvinyl chloride (PVC) and is adjustable to suit a range of patient sizes. Hook and loop fastening is fixed to the PTEG surface to assist with securing the coils onto the support. The coil support for pelvic imaging is shown in figure 2.

The head and neck coil support is manufactured from PTEG and secured onto an in-house manufactured MRI compatible head board (Fig. 3).

1 **(1A)** Medibord RT flat couch top **(1B)** access to head coil fixtures **(1C)** retaining access to coil securing fixtures and utilizing these fixtures for securing the couch top in position.

2 **(2A)** In-house manufactured coils support for pelvis imaging **(2B)** showing the couch securing mechanism and adjustable size.

3 In-house manufactured coils support for brain and head and neck imaging.

MRI safety

From the outset, it was clear that education and adjustment was needed to safely introduce an MRI Suite in the center of a clinical radiotherapy treatment center. Considerations for access management to the MRI control area, were new concepts for radiotherapy staff who were more familiar with the model that any hazard was removed when the power was switched off. Management of projectile hazards was also of concern. The MRI Suite control room door is key-coded to enable controlled access to the MRI control room and so to the MRI examination room. Early incidents of wiped credit cards and stopped watches served to underline the new working practices required.

Clinical preparation

Development of radiotherapy specific MRI protocols was based heavily on those developed in Umea University, who provided extensive informal mentoring support in the set-up of our service.

Prostate

The first patient cohort to receive MRI RT planning acquisitions was prostate patients. Two acquisition sequences were used: a 3D T2-weighted Sampling Perfection with Application optimized Contrasts using different flip angle Evolution (SPACE) sequence which was optimized to image the entire patient outline with a small voxel size (1.2 x 1.2 x 1.7 mm^3) and a high bandwidth to minimize geometric distortion, and a small FOV T2-weighted Turbo Spin Echo (TSE) sequence. The SPACE sequences has since been further optimized and the TSE sequence replaced with a Multi-Echo Data Image Contribution (MEDIC) sequence which is acquired over a smaller field of view to assist with the definition of the in-slice boundary of the prostate capsule.

A typical patient set-up is shown in figure 4, with details of the current acquisition protocols.

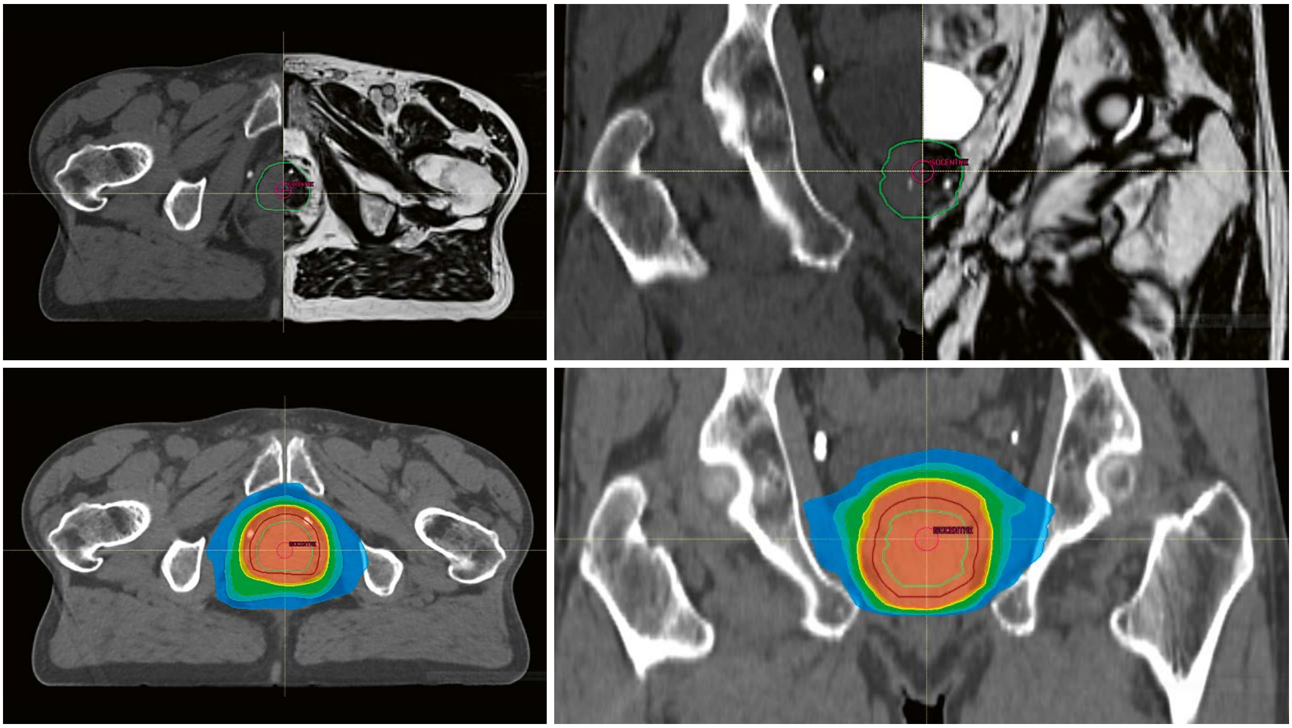
Prostate delineation protocols were developed with the help of Radiologist input. This inter-disciplinary team identified a difference in imaging task between diagnosis and delineation.

The experience of a radiologist identified the regions of disease within the prostate, but did not need to identify the boundary of the prostate gland, whereas a clinical oncologist needs to accurately delineate the boundary of the prostate gland. Cross disciplinary learning produced guidelines on prostate delineation based on MRI when fused with a planning CT. Methods of managing differences in patient anatomy between the MRI and CT scanning sessions were developed. There are inevitable patient set-up differences, both in posture and internal anatomy position. Rigid registration can take account of postural differences, but cannot completely compensate for differences in internal anatomy caused by changes in bowel and bladder filling. As the CT scan is used as the basis of the treatment plan and the reference image set for image guided radiotherapy, any differences in anatomy between CT and MRI tend to be compensated for by reverting to the CT anatomy as the gold standard. This inevitably compromises the added benefit of the MRI acquisition and results in an 'MRI guided CT delineation' for prostate GTV with OARs delineated on the CT scan. This means that the excellent MRI soft tissue image quality is not always able to be used to its full potential, providing experiential evidence of the benefit of an MR-only patient pathway. A typical CT-MRI image registration for a prostate patient, and the resultant dose distribution are shown in figure 5.

The clinical service was quickly extended to gynecological EBRT sites in January 2010. It was found that the same T2 3D SPACE acquisition protocol was suitable for cervix and uterus visualization. The acquisition sequences have now further developed and include two 2D sequences to assist with delineation, as shown in Table 1.

4 Typical patient set-up for prostate MRI acquisition and MRI acquisition parameters.

Sequence name	SPACE tse_vfl	MEDIC
Echo time	211 ms	22 ms
Repetition time	1500 ms	674 ms
Flip angle	150°	28°
Bandwidth	601 Hz/px	190 Hz/px
Orientation	Axial	Axial
Dimension	3D	2D
Field of View	450 x 447.3 mm^2	260 x 260 mm^2
Number of slices	120	34
Voxel size	1.4 x 1.4 x 1.5 mm^3	1.3 x 1.0 x 3.0 mm^3



5 CT-MRI image fusion with delineation and VMAT dose distribution.

Sequence name	SPACE tse_vfl	TSE	TSE
Echo time	165 ms	102 ms	101 ms
Repetition time	2000 ms	9840 ms	6300 ms
Flip angle	150°	150°	150°
Bandwidth	651 Hz/px	140 Hz/px	150 Hz/px
Orientation	Axial	Sagittal	Axial
Dimension	3D	2D	2D
Field of View	320 x 320 mm^2	290 x 280 mm^2	260 x 260 mm^2
Number of slices	144	28	45
Voxel size	1.3 x 1.3 x 1.5 mm^3	1.1 x 1.1 x 4.0 mm^3	1.0 x 1.0 x 4.0 mm^3

Table 1: MRI acquisitions for treatment planning of gynecological tumors.

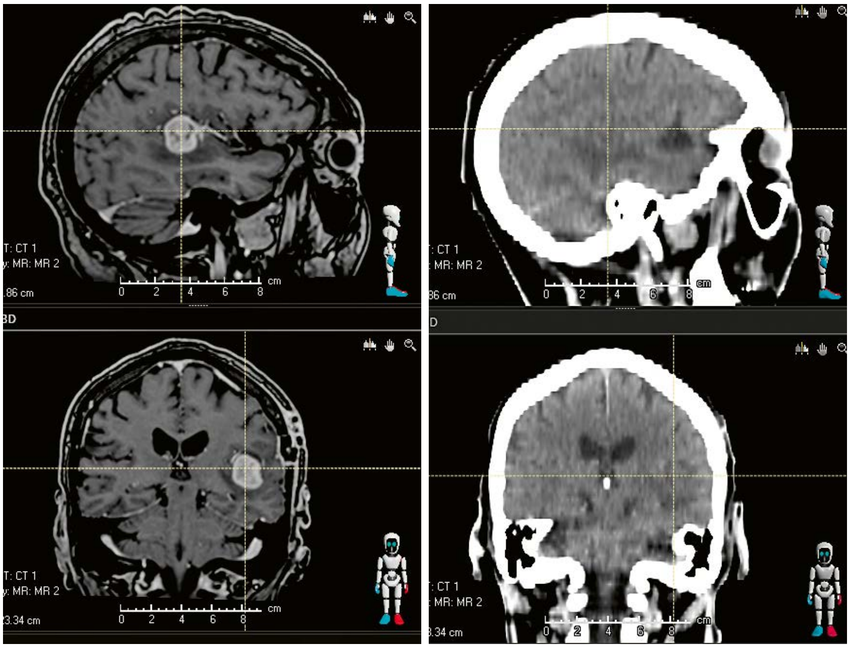
Brain

MRI imaging for selected brain tumors was introduced in January 2011. Patients are scanned without the immobilization device so that the head coil can be used.

A T1 axial 3D sequence is used for delineation of the GTV. Typical patient images and the MRI sequence parameters are shown in figure 6.

Head and neck

The introduction of MRI imaging for oro and hypopharyngeal tumors began in April 2011. Two sequences were developed to assist with GTV delineation and nodal and organ at risk delineation. A T1 VIBE post contrast acquisition was used to delineate GTV and a T2 sequence to delineate lymph nodes and organs at risk. Figure 7, shows a typical patient set-up and coil arrangement utilizing the in-house manufactured coil support. A second flex coil may be positioned over the patient's shoulders if required. The MRI acquisition parameters are also shown in figure 7 and typical patient images and dose distribution shown in figure 8.

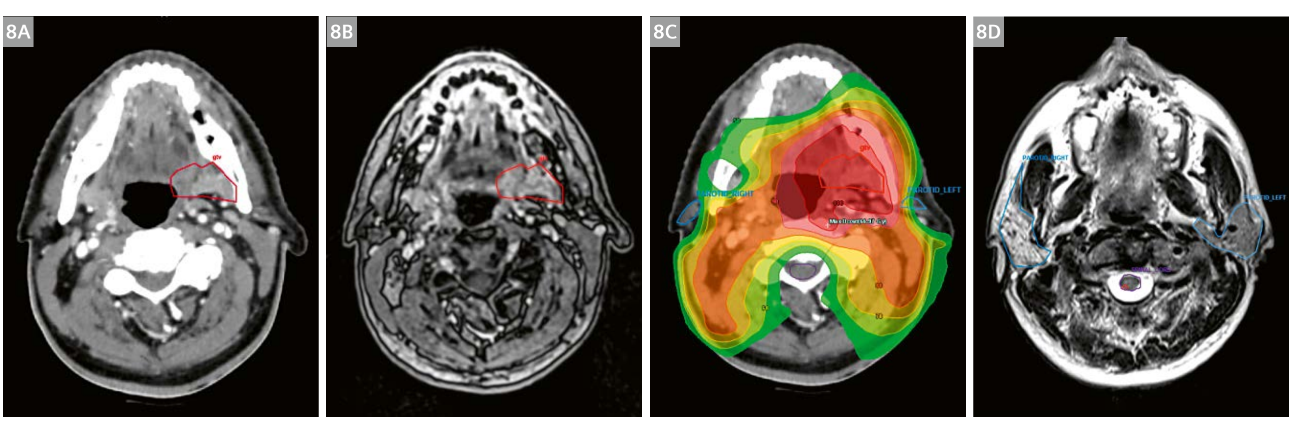


Sequence name	fl3d_vibe
Echo time	2.39 ms
Repetition time	9.00 ms
Flip angle	12°
Bandwidth	210 Hz/px
Orientation	Axial
Dimension	3D
Field of View	250 x 250 mm^2
Number of slices	192
Voxel size	1.1 x 1.0 x 1.0 mm^3

6 Soft tissue detail on MRI [LHS] and CT [Center] with MRI parameters shown on RHS.

7 A typical head and neck coil arrangement and MRI acquisition parameters.

Sequence name	fl3d_vibe	TSE
Echo time	2.39 ms	89 ms
Repetition time	9.00 ms	6000 ms
Flip angle	12°	150°
Bandwidth	210 Hz/px	159 Hz/px
Orientation	Axial	Axial
Dimension	3D	2D
Field of View	250 x 250 mm^2	310 x 271.25 mm^2
Number of slices	224	70
Voxel size	1.1 x 1.0 x 1.0 mm^3	1.1 x 0.8 x 3.0 mm^3



8 Typical image set **(8A)** CT, **(8B)** T1w VIBE **(8C)** dose distribution **(8D)** T2w TSE.

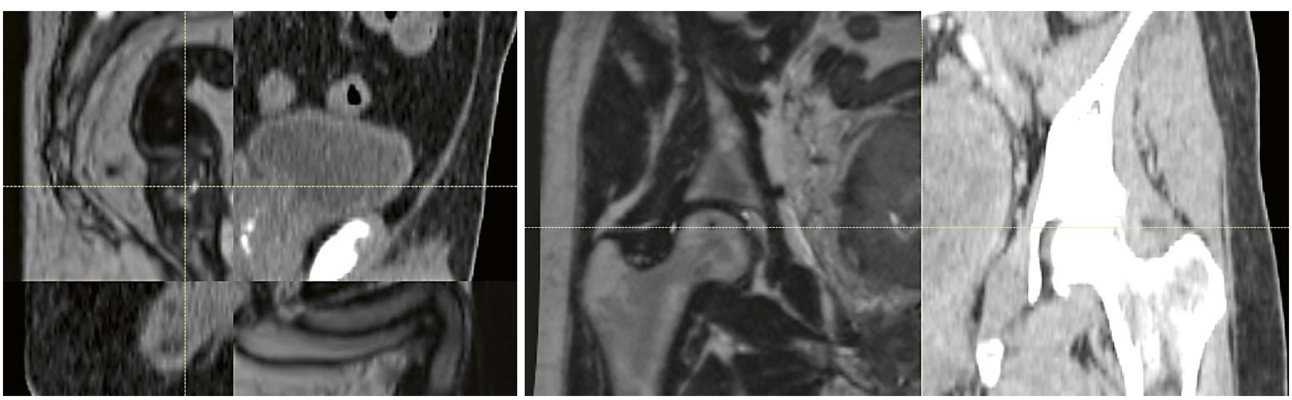
Rectum

Routine MR imaging for rectal cancer patients was introduced in April 2018. With MRI planning scans for anus patients then following in September, 2018. Patient set-up is similar to that for prostate patients.

The MRI acquisition parameters are shown for rectum patients in Table 2 and for anus patients in Table 3. A typical example of CT-MRI image registration for planning of a rectal cancer is shown in figure 9.

Sequence name	SPACE tse_vfl	TSE	TSE
Echo time	211 ms	102 ms	101 ms
Repetition time	1500 ms	9840 ms	6300 ms
Flip angle	150°	150°	150°
Bandwidth	601 Hz/px	140 Hz/px	150 Hz/px
Orientation	Axial	Sagittal	Axial
Dimension	3D	2D	2D
Field of View	450 x 447.3 mm^2	280 x 280 mm^2	260 x 260 mm^2
Number of slices	144	28	45
Voxel size	1.4 x 1.4 x 1.5 mm^3	1.1 x 1.1 x 4.0 mm^3	1.0 x 1.0 x 4.0 mm^3

Table 2: MRI acquisitions for treatment planning of rectal tumors.



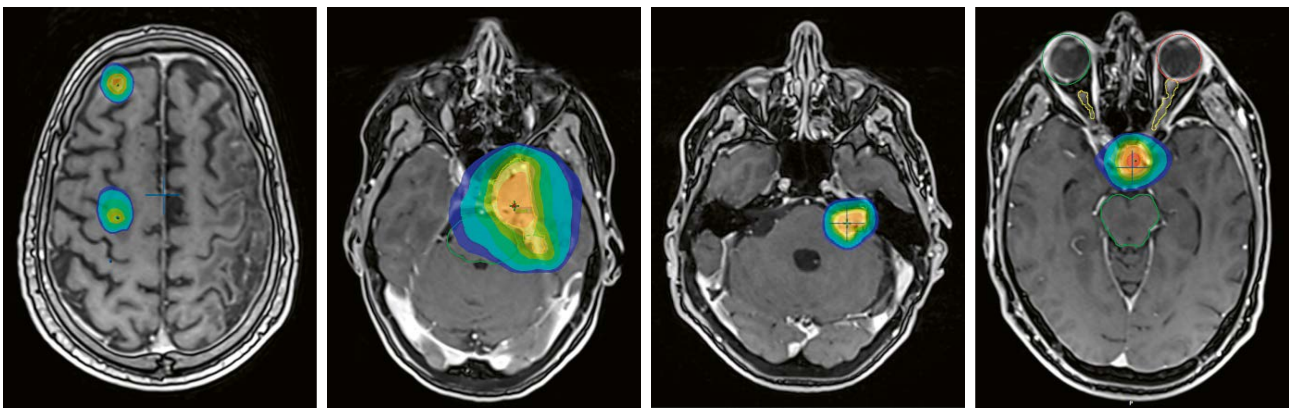
9 MRI-CT fusion for rectum and anus.

Sequence name	SPACE tse_vfl	TSE	TSE
Echo time	165 ms	102 ms	101 ms
Repetition time	2000 ms	9840 ms	6300 ms
Flip angle	150°	150°	150°
Bandwidth	651 Hz/px	140 Hz/px	150 Hz/px
Orientation	Axial	Sagittal	Axial
Dimension	3D	2D	2D
Field of View	320 x 320 mm^2	280 x 280 mm^2	260 x 260 mm^2
Number of slices	144	28	45
Voxel size	1.3 x 1.3 x 1.5 mm^3	1.1 x 1.1 x 4.0 mm^3	1.0 x 1.0 x 4.0 mm^3

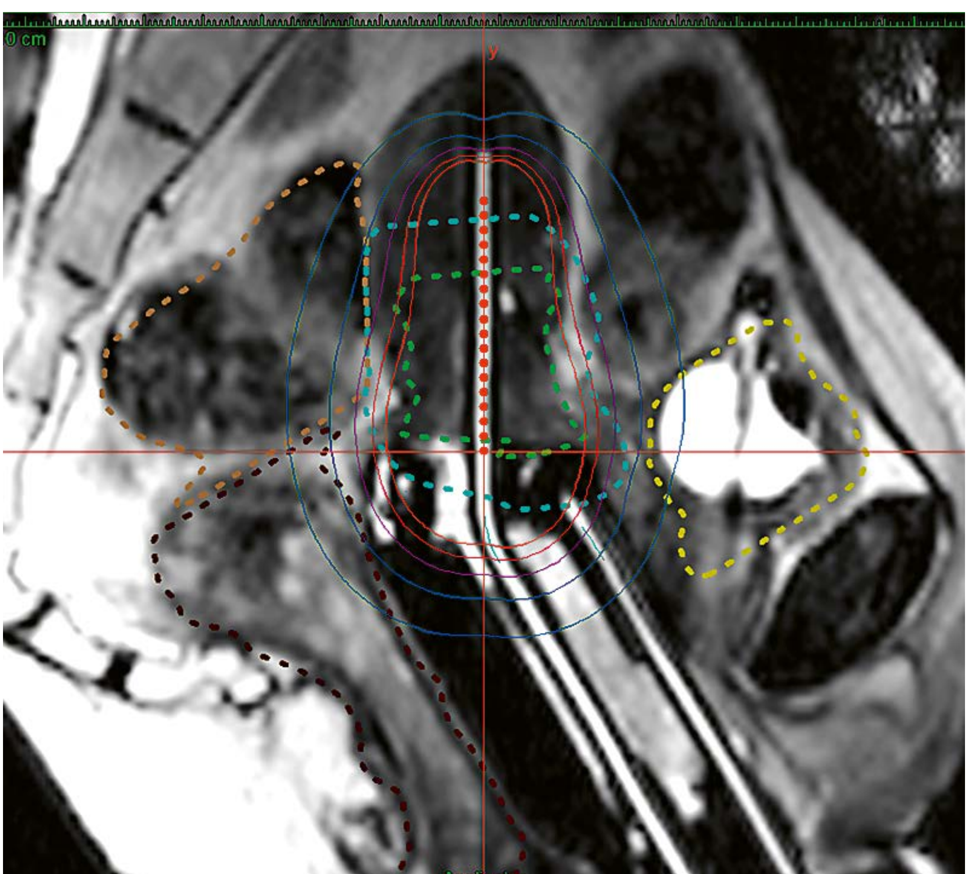
Table 3: MRI acquisitions for treatment planning of anal tumors.

SRS Brain

Newcastle is one of 17 Cancer Centers in England commissioned by NHS England to deliver Stereotactic RadioSurgery (SRS) and has been treating SRS patients since June 2015. Rapid access to planning MRI scans is essential to delivery of this service, particularly for patients travelling large distances. A range of MRI sequences are acquired, often tailored to the specific clinical presentation and vitally supported by neuroradiologists. Figure 10 shows a range of SRS brain tumors with the MRI acquisition image and the treatment dose distribution.



10 SRS brain treatments showing a range of treatment sites with the dose distribution.



11 MRI planning image showing a cervical ring brachytherapy treatment. The dashed lines show the clinical delineations and the solid lines the brachytherapy dose distribution.

Brachytherapy

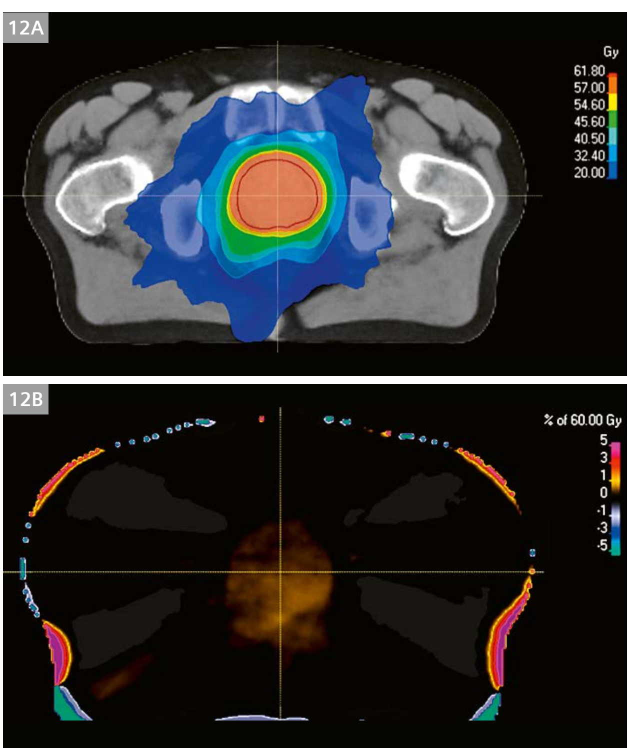
MRI acquisitions for brachytherapy post-planning for prostate I-125 implants began in February 2010, with MRI-only planning for cervix brachytherapy being implemented in September, 2011. MRI-only planning for vaginal vault brachytherapy treatments was introduced in July, 2012 when MRI was also introduced as a position check for vaginal vault applicator insertions for patients with intermediate and high risk endometrial cancer. Figure 11 shows a brachytherapy treatment for cervical cancer.

MRI-only planning

Our growing experience in CT-MR fusion for radiotherapy delineations emphasized the compromises that were necessary to account for differences in patient position and preparation between the CT and MRI imaging sessions. This was resulting in a limitation of the benefit of MRI as the CT image set was used as the standard where there were anatomical discrepancies between the CT and MRI. Feedback from Clinical Oncologists described increasing frustration at the compromises that were being imposed by limitations in the technique. NCCC has been investigating the technical development of an MR-only patient pathway since 2016 with research partners in Australia, UK and Sweden. Conventional CT-MR based radiotherapy planning utilizes the superior soft tissue provided by the MRI for target and OAR delineation, and the CT image to account for different types of tissue in the dose calculation. An MR-only pathway requires an appropriate dataset for dose calculation, a synthetic CT, and the NCCC research group have investigated the accuracy of available algorithms [2].

MR also suffers from geometric distortion, which is of some concern in radiotherapy planning image sets. A dedicated large field of view distortion phantom and automated analysis software was evaluated [3] and is now used in monthly quality assurance. Radiotherapy specific Quality Control programmes have been developed to ensure adequate geometric fidelity and demonstrate consistent performance of the clinical MR scanner. MR-only pathways are available in some European radiotherapy centers using X-ray IGRT treatment machines, but there is an important difference in the treatment pathway between these centers and NCCC. Prior to radiotherapy treatment being delivered at each visit, an imaging session is performed on the treatment machine to ensure that the patient is set-up and aligned as accurately as possible. In the existing clinical centers in Europe, this is achieved using fiducial markers, whereas image matching using soft tissue anatomy is used in Newcastle, sparing the patient the procedure required to insert fiducial markers. This means that the MRI image used to develop the treatment plan can be used as a reference image for the on-treatment image verification.

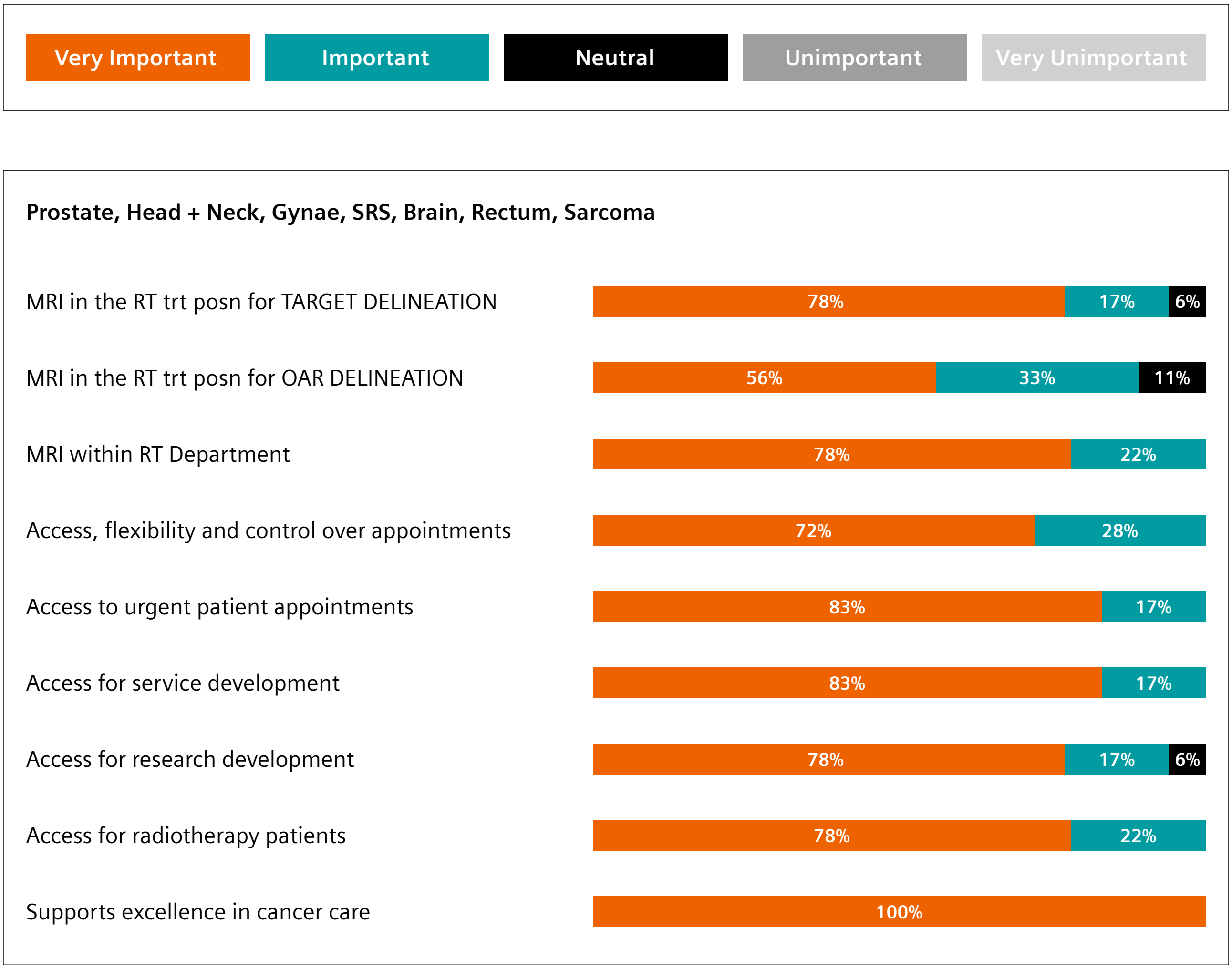
Our research experience coupled with our clinical experience means we felt confident in making the step from research to routine for MR-only planning for prostate patients. Our first MR-only prostate patients were treated in January 2019. Figure 12 shows the clinical dose distribution on the synthetic CT and the dose difference between the clinical plan and the QA plan calculated on the back-up CT.



12 First MR-only prostate patient – dose distribution **(12A)** and dose difference to CT **(12B)**.

Planning for the future

As the replacement date of our radiotherapy MRI approached, MR acquisition activity was not enough to justify a second purchase and it was important to capture the clinical opinion of the role of MR in radiotherapy planning. A survey of Consultant Clinical Oncologists in NCCC was performed where participants were asked to score a range of statements on a five point scale for the treatment sites which were routine at the time of the survey [4]. The five point scale is shown on the next page.



13 Responses for external beam treatment sites where a planning MRI is acquired.

The response rate was 73% and figure 13 shows the results for external beam treatment sites which include a planning MRI.

The survey showed an overwhelmingly positive response for sites which currently receive planning MRI scans. When asked how important it as to acquire MRI scans in the treatment position for target and OAR delineation, no ***Unimportant*** or ***Very Unimportant*** responses were received. The ***Neutral*** responses referred to Brain cases, where it was felt that although MRI is ***Very Important***, the patient position is less so, as rigid registration within the skull offers clinically acceptable results. There was also very strong support for the planning MRI scanner to be located within the radiotherapy department.

Summary

NCCC were one of the first UK cancer centers to install a dedicated MRI scanner for radiotherapy planning, in 2009. The clinical workload and clinical scope has significantly increased over the first 10 years so that over 35% of radical patients in Newcastle now receive an MRI to improve their planning pathway. Practices and equipment have developed greatly over the past ten years and manufacturers now offer commercial coil bridges and supports, however our experience with in-house developments may be useful on further developing commercial products. There was overwhelming clinical support to replace our radiotherapy MRI scanner and we are now looking forward to extending our MR-only pathway for prostate patients to other treatment sites, cementing MRI as indispensable to the radiotherapy pathway. The image (right) shows the NCCC MR in RT Team.

Acknowledgments

The authors would like to acknowledge the contribution of Jill McKenna to the development and introduction of the NCCC MRI service.

References

1 EC Harron, MJ Firbank, J McKenna, HM McCallum R Mohanraj. Evaluation of MRI distortion correction for use in radiotherapy treatment planning. Clinical Oncology 23(3), 2011.
2 Jonathan Wyatt, Jason A Dowling, Charles G Kelly, Jill McKenna, Emily Johnstone, Richard Speight, Ann Henry, Peter B Greer and Hazel M McCallum. Investigating the generalisation of an atlas-based synthetic-CT algorithm to another center and MR scanner for prostate MR-only radiotherapy. Physics in Medicine and Biology, 62(24), 2017.
3 Jonathan Wyatt, Stephen Hedley, Emily Johnstone, Richard Speight, Charles Kelly, Ann Henry, Susan Short, Louise Murray, David Sebag-Montefiore, Hazel McCallum. Evaluating the repeatability and set-up sensitivity of a large field of view distortion phantom and software for magnetic resonance-only radiotherapy. Physics and Imaging in Radiation Oncology, 6, 2018.
4 HM McCallum, JJ Wyatt, J McKenna, CG Kelly, CP Walker. A compelling case for MRI in RT? The Newcastle experience. Poster presentation at Institute of Physics and Engineering in Medicine: MR in the planning, delivery and monitoring of radiotherapy conference, Edinburgh, March 2017.

Contact

Dr. H. M. McCallum
Consultant Clinical Scientist
Radiotherapy Physics
Northern Centre for Cancer Care,
Freeman Hospital
Newcastle upon Tyne, NE7 7DN
UK
Tel.: +44 (0)191 213 8112
hazel.mccallum@nuth.nhs.uk

Dr. Rachel Pearson
Consultant Clinical Scientist
Radiotherapy Physics
Northern Centre for Cancer Care,
Freeman Hospital
Newcastle upon Tyne, NE7 7DN
UK
Tel.: +44 (0)191 213 8521
rachel.pearson@nuth.nhs.uk

The NCCC MRI Team [left to right] **Timothy Dowling** and **Steve Harris**, Senior MRI Imaging Radiographers; **Rachel Pearson**, Consultant Clinical Oncologist; **Rachel Brooks**, Research and Development Clinical Specialist Radiographer; **Iraje Ahmed**, MRI Imaging Radiographer; **Elizabeth Raven**, Superintendent Treat-'ment Radiographer; **Hazel McCallum**, Consultant Clinical Scientist; **Karen Pilling**, Clinical Lead Superintendent Radiographer; **Serena West**, Imaging Superintendent Radiographer; **Jonathan Wyatt**, Clinical Scientist.