Article:
Speight, R, Dubec, M, Eccles, CL et al. (7 more authors) (2021) IPEM topical report: guidance on the use of MRI for external beam radiotherapy treatment planning. Physics in Medicine & Biology. ISSN 0031-9155

https://doi.org/10.1088/1361-6560/abdc30

IPEM topical report: guidance on the use of MRI for external beam radiotherapy treatment planning

To cite this article before publication: Richard Speight *et al* 2021 *Phys. Med. Biol.* in press https://doi.org/10.1088/1361-6560/abdc30

IPEM topical report: Guidance on the use of MRI for external beam radiotherapy treatment planning

Contact Email

richard.speight@nhs.net

Author list:

Richard Speight, Leeds Cancer Centre, Leeds Teaching Hospitals NHS Trust, Leeds, UK

Michael Dubec, The Christie NHS Foundation Trust and the University of Manchester, Manchester, UK

Cynthia L Eccles, The Christie NHS Foundation Trust and the University of Manchester, Manchester, UK

Ben George, University of Oxford and GenesisCare, Oxford, UK

Ann Henry, Leeds Cancer Centre, Leeds Teaching Hospitals NHS Trust and University of Leeds, Leeds, UK

Trina Herbert, Royal Marsden NHS Foundation Trust, London, UK

Robert I Johnstone, Guy's and St. Thomas' NHS Foundation Trust, London, UK

Gary P Liney, Ingham Institute for Applied Medical Research and Liverpool Cancer Therapy Centre, Liverpool, Sydney, NSW 2170, Australia

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

Maria A Schmidt, Royal Marsden NHS Foundation Trust and Institute of Cancer Research, London, UK

Note: this work is part of an IPEM working party and work was shared between the group equally. The working party was chaired by Richard Speight.

ORCID iDs

Richard Speight https://orcid.org/0000-0001-8981-1640

Michael Dubec https://orcid.org/0000-0001-7758-3310

Cynthia L Eccles https://orcid.org/0000-0002-5445-5428

Ann Henry https://orcid.org/0000-0002-5379-6618

Robert I Johnstone https://orcid.org/0000-0003-2711-9469

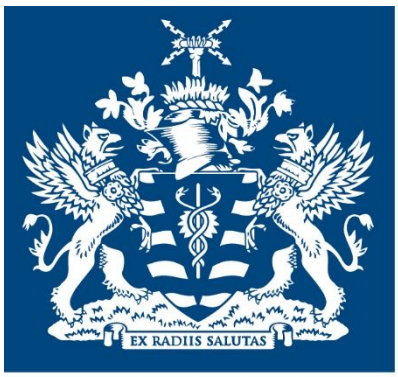
Hazel McCallum https://orcid.org/0000-0001-5121-2335

Maria A Schmidt https://orcid.org/0000-0001-8993-5301

Endorsed by:

This guidance has been endorsed by the Institute of Physics and Engineering in Medicine (IPEM), the Society and the College of Radiographers (SCoR) and the Faculty of Clinical Oncology of The Royal College of Radiologists (RCR).

SoR
THE SOCIETY OF RADIOGRAPHERS



Clinical Oncology
The Royal College of Radiologists

Conflict of interest:

none

Keywords

MRI, radiotherapy treatment planning, guidelines

Abstract

This document gives guidance for multidisciplinary teams within institutions setting up and using an MRI-guided radiotherapy (RT) treatment planning service. It has been written by a multidisciplinary working group from the Institute of Physics and Engineering in Medicine (IPEM). Guidance has come from the experience of the institutions represented in the IPEM working group, in consultation with other institutions, and where appropriate references are given for any relevant legislation, other guidance documentation and information in the literature.

Guidance is only given for MRI acquired for external beam RT treatment planning in a CT-based workflow, i.e. when MRI is acquired and registered to CT with the purpose of aiding delineation of target or organ at risk volumes. MRI use for treatment response assessment, MRI-only RT and other RT treatment types such as brachytherapy and gamma radiosurgery are not considered within the scope of this document. The aim was to produce guidance that will be useful for institutions who are setting up and using a dedicated MR scanner for RT (referred to as an MR-sim) and those who will have limited time on an MR scanner potentially managed outside of the RT department, often by radiology. Although not specifically covered in this document, there is an increase in the use of hybrid MRI-linac systems worldwide and brief comments are included to highlight any crossover with the early implementation of this technology.

In this document, advice is given on introducing a RT workload onto a non-RT-dedicated MR scanner, as well as planning for installation of an MR scanner dedicated for RT. Next, practical guidance is given on the following, in the context of RT planning: training and education for all staff working in and around an MR scanner; RT patient set-up on an MR scanner; MRI sequence optimisation for RT purposes; commissioning and quality assurance (QA) to be performed on an MR scanner; and MRI to CT registration, including commissioning and QA.

Acronyms used

AAPM	American Association of Physicists in Medicine
ACR	American College of Radiology
B0	the static magnetic field of an MR scanner
BW	bandwidth

CT	computer tomography
DICOM	Digital Imaging and Communications in Medicine
DSC	Dice similarity coefficient
ECG	electrocardiogram
FOV	field of view
fs	fat saturation
FLAIR	fluid attenuated inversion recovery
FSE	fast spin echo
GE	gradient echo
GTV	gross tumour volume
IPEM	Institute of Physics and Engineering in Medicine
IV	intravenous
MDA	mean distance to agreement
MHRA	Medicines and Healthcare products Regulatory Agency
MRCAA	MR Controlled Access Area
MR	magnetic resonance
MRI	magnetic resonance imaging
MR-sim	MR-simulator
MRSE	MR Safety Expert
NHS	National Health Service
OAR	organs at risk
PACS	Picture Archiving and Communication System

pix	pixel
ppm	parts per miliion
QA	quality assurance
RCR	Royal College of Radiologists
RIR	rigid image registration
ROI	region of interest
RT	radiotherapy
SAR	specific absorption rate
SCoR	Society and the College of Radiographers
SE	spin echo
SNR	signal to noise ratio
SRS	stereotactic radiosurgery
TE	echo time
TPS	treatment planning systems
TRE	Target registration error

Section 1 Clinical introduction and evidence base

Key messages of section:

- *MRI provides superior soft tissue contrast than CT, so it can increase target and organ at risk delineation accuracy, potentially improving patient outcomes.*
- *MRI is increasingly being incorporated into the radiotherapy (RT) workflow.*
- *This document provides concise multidisciplinary guidance to ensure safe and effective implementation of MRI for external beam RT. MRI use for treatment response assessment, brachytherapy and other treatment types are beyond the scope of this document.*
- *MRI can be acquired from a dedicated MRI scanner for RT or from a diagnostic scanner with input from RT staff.*

Radiotherapy (RT) is one of the most effective cancer treatments available and 40% of cancer patients will undergo radiation treatment as part of their cancer care package (NHS England 2018). Cancer survival is now at its highest ever with more than half of people living at least ten years beyond initial diagnosis (CRUK 2020). With more people living with and beyond cancer, it is increasingly recognised that reducing RT-related side effects and improving quality of life are often as important as survival outcomes.

The RT workflow traditionally uses CT imaging for treatment planning and dose calculation. MRI provides superior soft tissue contrast when compared to CT and is increasingly used to accurately identify tumours both at RT planning and during treatment delivery (Liney *et al* 2018, Chandarana *et al* 2018).

It has been recognised that the greatest improvements in RT over the next decade are likely to be due to imaging developments. This led to the recommendation that for each 2 to 4 million people served by an RT centre there should be at least 0.7 of dedicated MR scanner's imaging time available to guide treatment planning (Cancer Research UK 2015). Implementation of this recommendation has been slow, with a recent Institute of Physics and Engineering in Medicine (IPEM) survey demonstrating that the provision of dedicated MR scanners within RT departments was limited to 2 out of 71 UK centres in 2018 (Speight *et al* 2019). A key finding of this survey was that there was a large variability in implementation of many aspects of MRI for RT which was thought to be, in part, due to a lack of guidance or consensus in the literature. The aim of this document is to provide such guidance, to aid implementation of MRI for RT for a MRI-CT workflow. The guidance has been developed by IPEM as a UK national professional body, however most of the guidance is valid internationally and is not UK

specific. The main exceptions to this are the discussion on MR safety in terms of the legislation, guidance and the terminology used to define areas and personnel in section 4. This document was written by, and is aimed at, a multi-disciplinary audience. For clarity throughout this document we refer to persons with adequate physics knowledge in MRI or RT, along with adequate experience to utilise this knowledge in a clinical setting, as a clinical scientist (MR) and clinical scientist (RT) respectively.

Section 2 describes the processes required to introduce RT workload onto an MR scanner within a radiology department. Section 3 advises on the procurement and installation of an MR scanner specifically to deliver an RT planning service, referred to as an MRI simulator (MR-sim). Section 4 outlines the fundamentals of MR safety and describes the UK legislation and guidelines used to provide an institutional framework for safe MR imaging. Section 5 addresses training and education across all staff groups. Section 6 describes patient set-up for MRI simulation. Section 7 advises on the MRI sequence requirements for RT planning. Section 8 describes the quality assurance (QA) requirements for the use of MRI in RT. Lastly, Section 9 addresses MRI to CT image registration methods and the commissioning and QA for image registration.

Section 2 Introducing RT workload to a scanner not dedicated for RT

Key messages of section:

- *Building a collaboration between RT and radiology teams is vital.*
- *Designing and evaluating MRI sequences used in RT treatment planning is essential, particularly regarding geometric distortion.*
- *Use of a flat couch top is recommended for extra-cranial sites.*
- *Data transfer and management must be carefully considered.*

2.1 Introduction

This section outlines approaches to introducing a RT planning workload on a non-RT dedicated MR scanner, with the intention of registering an MR image with a planning CT scan, using the most efficient resources and QA processes, as a route to progressing towards a more comprehensive MRI-CT planning service. There is a range of approaches, from using a diagnostic acquisition with careful

consideration of the limitations, to acquiring a dedicated RT image using a RT-specific protocol. In all approaches, clinical training on interpretation and delineation on MR images is essential. For further recommendations on training see Section 5.3.

2.1.1 Using diagnostic MRI images

An initial approach, which requires a minimum of preparation and resources, is to use the standard diagnostic patient setup and MRI sequences, in the RT treatment planning process. Collaboration with radiology is important as diagnostic sequences can be modified in order to be useful for diagnostic and radiotherapy treatment planning purposes. This is particularly appropriate for brain imaging.

While there is obvious appeal to this approach, it is important to follow the recommendations on acquisition parameters shown in Table 1 and to consider the differences between the typical diagnostic and RT set-up and the consequent limitations that these differences may cause. The results of these considerations should be documented and any limitations on the utility of the diagnostic images should be discussed with the clinical oncology team. It should be noted that diagnostic practice may modify sequence parameters to suit patient anatomy and capabilities. Therefore it may be necessary to review sequences on a patient by patient basis.

If consistent imaging parameters cannot be achieved for all patients, the considerations listed below should be evaluated and documented for each MR sequence used for RT planning.

Parameter	Recommended values	Comment
Receiver bandwidth	Reduce fat-water chemical shift to displacements of 1 mm or less.	The bandwidth determines the strength of the readout gradient. A low bandwidth will increase geometric distortion and the fat-water shift, which will compromise the geometric accuracy of images. Note that high bandwidths compromise the signal to noise ratio (SNR) which may need to be compensating for.
Slice thickness	2 mm is a useful guide, but it should be comparable to CT.	Ensure partial volume effects in MR are no worse than those of CT acquisition. Diagnostic scans typically have thicker slices, to improve SNR.
Slice gap	Zero.	It is important that all anatomy is contained within the image set as non-zero slice gaps result in significant image degradation when registered with the planning CT. Diagnostic

		scans typically have non-zero slice gaps to reduce artefacts.
Field of view	Large enough to image required anatomy and sufficient peripheral anatomy to enable accurate and unambiguous image registration.	It is essential that sufficient anatomy is imaged to permit visual verification of the accuracy of image registration. Some bony anatomy may be essential for MRI-CT registration.
3D vs 2D acquisition	Use 3D acquisition if possible.	It is easier to achieve isotropic resolution and to use 3D geometric distortion correction.
Post-processing for distortion correction	Application of geometric distortion correction for all acquisitions is essential. Use 3D distortion correction, if available.	3D distortion correction is more effective than 2D for both 2D and 3D acquisitions.

Table 1. Guidance on MR imaging parameters.

Diagnostic MR images are most often used for cranial RT planning (Speight *et al* 2019), where the size and geometry of the cranium allows easy detection of excessive geometric distortion. The cranium also provides immobilisation of tissue within it and anatomy for rigid image registration (RIR) with the planning CT and visual verification of that registration. Outside the cranium, there are significant anatomical positional differences between imaging on a curved couch and flat couch, severely limiting the performance of RIR. The potential for significant geometric distortion is also higher, due to the larger field of view (FOV). For these reasons, use of extra-cranial diagnostic MRI acquisitions with image registration for RT planning is not recommended.

2.1.2 Developing RT-specific approaches

In order to address some of the image acquisition limitations described above, when MR capacity allows a dedicated MR scan for RT purposes it is necessary to design RT-specific MRI scan protocols. The key parameters for such protocols are shown in Table 1, along with recommended values. Introducing a flat couch top greatly improves the reproducibility of patient setup compared to the planning CT scan, enabling the MRI planning service to be extended to extra-cranial sites. Advice for a range of anatomical sites is given in Section 6.

The centre of the region of interest should be positioned at the imaging isocentre and the couch position should be the same for all acquired sequences. This will minimise the residual geometric distortion over the most critical region across all acquired sequences.

2.2 Building collaboration between RT and radiology

Collaboration between RT and radiology disciplines is a very important aspect of the successful introduction of MRI in RT using a radiology scanner. Collaboration at an early stage with diagnostic radiographers, radiologists and, if available, clinical scientists (MR) allows time for radiology and RT staff to understand the different clinical requirements for diagnostic and RT planning MRI acquisitions.

A discussion on the type of image interpretation that is performed by a radiologist and a clinical oncologist can be extremely useful. In the experience of the centres represented by this working party, a radiologist searches for abnormal tissues in order to make a diagnosis, whereas an oncologist searches for the boundary of the abnormal tissue to delineate a tumour volume. The radiologist requires excellent tissue differentiation but does not require a reproducible patient position or minimal geometric distortion. The oncologist requires the patient to be in a reproducible position to assist with the accuracy of image registration with CT, excellent geometric fidelity and adequate image quality to visualise the tissue boundaries for delineation.

Defining an appropriate MRI FOV for MRI-CT registration can pose a challenge between extending the imaged area to include anatomical features, to ensure unambiguous registration, and avoiding lengthy scan times. This can be particularly demanding for spine sequences where the robust identification of the relevant vertebrae can be difficult with a small MRI FOV. For spine imaging, it is suggested that a region is imaged that includes two vertebrae above and below the region of interest and that the lateral FOV contains sufficient anatomy to be able to uniquely identify each vertebra.

It is vital to balance the importance of excellent image quality against a sufficient imaged volume to ensure accurate registration and sufficient geometric accuracy. Although many RT treatment planning systems (TPS) now support sagittal and coronal image sets, it is advantageous to include a transverse image set in the RT MRI protocol as it is still common practice to delineate and review anatomy on a transverse presentation. It is recommended to have a high in-slice resolution in the transverse plane for this purpose.

Training for the RT team in interpretation and delineation of MR images is essential. Training from radiologists provides important familiarisation in image interpretation for the RT team and builds

relationships which can provide ongoing support in developing the MRI for RT service. It is important to consider training when introducing each new treatment site.

It is very helpful to establish a collaborative working group between RT and radiology. This should include clinical directors, directorate managers and service managers to provide strategic direction and a commitment for support and resource between departments. Development of initial procedures and delineation guidelines are improved if therapeutic radiographers, clinical oncologists and clinical scientists (RT) have support from radiologists, diagnostic radiographers and clinical scientists (MR). It is wise to explore funding of radiology resource to ensure sustainability of support as the service develops.

2.3 Purchase of additional equipment

The use of a flat couch top is recommended to improve RIR between the planning CT scan and the MRI images. Further information on registration is given in Section 9. There are several commercially available MRI flat couch tops. An in-house manufactured flat couch top, such as a layer of rigid plastic, can be effective as a more budget-friendly starting point.

Use of RT immobilisation devices will improve the reproduction of RT treatment positions and can significantly improve RIR accuracy. It is essential that RT immobilisation devices are tested for MR safety status and safety prior to use – see Section 4. Knee rests and foot stocks are commonly manufactured from foam rubber or plastic, but they may be attached to rigid bases which include metallic or carbon fibre components. The moulding of vacuum bags should be performed outside the magnet room.

Installation of MR conditional lasers, used within their conditions, will improve the reproducibility of patient setup. However, the retrospective installation of lasers may pose a risk to the integrity of the Faraday cage and may not be feasible. In this case the internal scanner lasers may be used to assist with basic patient alignment.

2.4 MRI QA

Diagnostic MR scanners have a very heavy workload and arranging additional time to perform routine RT-specific QA may be challenging. The QA approach outlined in Section 8 should be followed for acceptance and commissioning new pathways. However, it is recognised that a proportionate

approach to routine QA would be sensible for on-going tests. If there is one patient per week scanned in the RT position, then a comprehensive monthly QA programme is not reasonable. We suggest that the frequency of QA is adjusted proportionately to patient workload, where a scanner workload of more than 10 patients scanned in the RT position per week would require the complete testing and frequency as described in Section 8 and a smaller workload would proportionately reduce the testing frequency. If a diagnostic MR scanner is used only for brain MRI scans, then additional RT-specific scanner QA tests are not required but patient-specific QA should be carried out (see below).

The following QA is recommended to be performed for each patient:

- Ensure that the orientation of the patient is correct and is accurately transferred to the TPS.
- Evaluate, at least qualitatively, MRI-CT image registration on the TPS (see section 9.3.4.1).
- Verify that the appropriate distortion correction has been applied (McWilliam *et al* 2018).

2.5 **RT staffing**

MRI for RT image acquisition workflow models should be discussed and agreed locally dependent on the local requirements and on the education, training and competence of professionals within the service. Here two staffing models are given as examples to help support the safe introduction of MRI for RT. The first being two therapeutic radiographers with pre-treatment imaging experience, for patient set-up, and a diagnostic radiographer, to oversee the acquisition. The second staffing model would be a therapeutic radiographer and a diagnostic radiographer with suitable training for both, so that each understands the requirements from both disciplines. Professional and clinical responsibilities must be carefully addressed if the accountability for an MRI acquisition for RT planning purposes were to be assumed solely by diagnostic radiographers. Advice on training is given in Section 5.3.

2.6 **Connectivity and data management**

Radiology and RT departments typically use separate scheduling systems that are unlikely to be integrated. If RT staff have access to the radiology system, then RT planning scans can be scheduled through this in discussion with the Radiology department. It is useful if the oncology information system can also be accessed from the radiology department. However, if RT and radiology systems are separate, then appointments will need to be booked in both systems. When scanning for RT planning purposes on a diagnostic MR scanner, all images acquired may be sent to PACS for storage.

In this case, a comment or label is useful to identify the MRI as an RT planning scan which may not by suitable as a diagnostic data set. The need for radiology reporting of planning MR acquisitions must be agreed for each treatment site and the decision documented. It is often considered unnecessary for a full radiological report to be produced, so an auto-report may be sufficient, with a generic text such as 'For RT planning only, will be reviewed by a clinical oncologist'.

Section 3 Planning the procurement and installation of an MR-sim

Key messages of section:

- *Site planning is very important and must be started early.*
- *At the planning stage it is vital that a multidisciplinary project team is established that represents all stakeholders.*
- *When evaluating new scanner options, produce a required scanner specification and quantitative scoring matrix to enable a fair comparison.*

3.1 Introduction

Procurement of an MR-sim is a complex procedure, in part due to the variety of options available. The choice of field strength for an MR scanner dedicated for RT is also complex with the most common options being 1.5 or 3 T. The primary differences being that 3 T offers higher SNR at the cost of an increased susceptibility effect (discussed in section 7.3). The suitability of the site where the MR scanner will be located must also be taken into account, in terms of provision of a safe workspace and of enabling the MR scanner to operate according to the manufacturer's specification. The aim of this section is to discuss a proposed process to decide what MR-sim is most appropriate for a given institution. This process is broken down into the following steps, some of which follow general procurement advice which should be available in each institution:

1. Establish a list of stakeholders in the new MR-sim and establish a multidisciplinary project team that fully represents and understands the needs of these stakeholders.
2. Assess the site planning manuals for all the MR-sims that are of interest, in order to determine the site planning specifications.
3. Produce an MR-sim specification to list the essential and desirable requirements for the scanner.

4. Using publicly available information, shortlist potential MR-sims that could meet the MR-sim specification.
5. Develop a quantitative scoring matrix.
6. Complete the scoring matrix for all shortlisted scanners by inviting vendors to respond to the MR-sim specification and carrying out site visits. Finally, make recommendations based on the result of the scoring matrix.

3.2 Establishing stakeholders and selecting a multidisciplinary project team

A list of stakeholder groups must be agreed and should include representation from all groups who will manage and use the images produced on the MR-sim. Once the stakeholder groups have been identified a project team should be established, including nominated people to represent the stakeholders. The project team can be sub-divided into a scanner evaluation team, who will perform the evaluation and make recommendations, a site planning team, who will ensure the scanner site meets the requirements of the users and scanner manufacturers, and a project board – more senior members of staff who will make decisions based on the scanner evaluation team's recommendations. The project team should have representation from the following staff groups: estates/equipment manager, procurement manager, clinical scientist (both RT and MR, if available), therapeutic and diagnostic radiographers, clinical oncologists and radiologists, management and research staff (if applicable).

3.3 Site planning specifications

Installation of an MR scanner poses different challenges compared to installation of more conventional RT equipment. For RT departments installing an MR-sim for the first time, it is possible that it will be installed within a suite that used to house a CT scanner. This leads to some specific problems, as CT scanners tend to have both a smaller physical footprint and require less space around them. Thus, the scanner rooms may be too small, leading to building work requirements to make the suite an appropriate size as well as enlarging access routes to fit the MR scanner into the desired location. In addition, CT suites require radiation shielding in the walls, floors and ceilings, whereas MR suites require a Faraday cage and, potentially, magnetic shielding in these locations instead, which

may require structural changes to the room. The process of locating a suitable hospital space and preparing it for an MR scanner is referred to as MR site planning.

Generic guidance for MR site planning has been available since the 1980's (Bronskill *et al* 1986). Specific advice for each make and model is given by manufacturers in a 'site planning manual'. This must be followed to ensure that the MR scanner will perform according to the specification provided by the manufacturer. To future proof the site, for example allowing a higher magnetic field strength for any subsequent MR scanner, it is advisable to have a safety margin on any parameter. Some of the aspects that need considering for site planning, that are potentially different to those for other RT equipment, are shown in Table 2.

Aspect to consider	Explanation of the importance
Space requirements	Ensure there is adequate space for all equipment including: MR scanner, MR Controlled Access Area, patient changing areas and secure lockers, toilet facilities, storage for consumable equipment, supporting plant (chillers, air conditioning) and auxiliary equipment necessary for RT purposes (flat couch tops, coil bridges, base plates, immobilisation devices). A suitable area must also be available for private discussion with patients such as for undertaking MRI safety questionnaires. Minimum sizes for scanner room, technical room and control room are provided by the manufacturers.
Building structural requirements	Including floor strength and materials to limit proximity to ferromagnetic materials within building fabric.
Sources of electromagnetic fields	All manufacturers require minimum distances to sources of mains frequency electromagnetic fields, for example transformers, high currents, etc.
Faraday cage requirements	If not designed and installed correctly then this can allow external noise to be picked up by the MR scanner.
Localisation laser requirements	Retrospective installation of lasers can damage an existing Faraday cage, with significant cost, so forward planning is recommended. Provision to switch off power to the lasers should be given, due to their potential as a source of electromagnetic noise. It is very helpful to install a laser power switch in the MRI Control Room.
Proximity to large moving metallic masses	Moving metallic masses affect the magnetic field and this can cause image artefacts. Examples include: linear accelerators, roads, car parks, lifts, etc.
Atmospheric requirements	MR scanners must be kept in very controlled conditions to work optimally. Examples include humidity and temperature which are limited to specific ranges.
Requirements for magnetic shielding	Adequate shielding is required to limit magnetic fields outside the MRI suite. This is important to limit exposure to the general public and other devices such as linacs and CT/PET/other MR scanners.
Implications of MRI suite design for safety	The MHRA recommendations for safe operation must be followed (see Section 4.2). A major safety concern is limiting access to the suite. Therefore, designing an MR Controlled Access Area is vital. All workflows should be considered to allow potential hazards to be identified and risks minimised.
The delivery route for equipment	Due to the large size of MR scanners, the delivery route must be carefully considered. If the installation will be in an existing building, this may involve work to remove sections of walls, etc.
Quench pipe routing out of the building	In the emergency case of a magnet quench, a quench pipe vents helium gas to the outside of the building. The quench pipe outlet must be located at an adequate height defined in the site planning manual, away from public areas. If the installation site is central in a building, then the quench pipe route becomes more complex and requires careful planning.
The delivery route for cryogens	Liquid helium is required in most MR scanners and this must be safely delivered to the MRI suite.
Requests for clearly labelled MR Safe or MR Conditional equipment	Mobile equipment that could potentially be taken into the MR scanner room should be MR Safe or MR Conditional (and used within its conditions) to reduce the risk of harm to patients and staff. Items to consider include gas canisters, chairs, trolleys, fire extinguishers, etc.

Provision for piped medical gasses	If required, provision for medical gases should be added at the design phase. A multidisciplinary team (including an anaesthetist if relevant) should consider all expected uses for the MRI suite to decide on the best location for these piped medical gases.

Table 2. Some aspects of site planning to consider in order for the MR-sim to operate optimally. Full details can be found in vendor-specific site planning manuals.

3.4 Establishing the clinical system requirements – MR-sim specification

The project team should determine the requirements for the MR-sim in order to satisfy the needs of all stakeholders. One of the first tasks is to determine the anatomical sites of interest. All sites that may be of interest over the lifetime of the scanner should be considered, in order to future proof the equipment. The requirements of the MR-sim should be collated into a single document – the specification. It is recommended that this is written in such a way that it can be sent to MRI vendors so that they may respond with how well their product meets the requirements. The specification should list the specific clinical and training requirements, possibly subdivided into essential and desirable requirements. These requirements will vary depending on the intended use of the equipment. This means that a definitive list cannot be recommended here, however some of the criteria that should be considered for the MR-sim specification are detailed in Table 3.

Primary criteria for consideration	**Sub-criteria for consideration and detail**
Clinical suitability	Ability to scan all anatomical sites in all required patient setup positions: consider current and future pathways and the required coil arrangements.
	Ability to use advanced techniques/equipment of clinical interest (MRI-only RT, reduced acoustic noise sequences, specific equipment to enhance patient experience, e.g. ambient room lighting, enhanced audio-visual entertainment system).
	Image quality requirements for each anatomical site.
	Access to all MRI sequences required for the range of anatomical sites, including specialized sequences such as physiological/metal artefact reduction sequences. Identification of all software packages/equipment required for the intended purposes of the scanner.
Technical suitability	MR-sim specifications: consider field strength, bore dimensions, imaging field of view, geometric distortion tolerances etc.
	Safety feature requirements.
	Ease of use for all end users (scanning patients/performing QA etc.). Are there any automated features that streamline current workflows?
IT requirements	DICOM connectivity.
	Compatibility with existing equipment: break down into all systems scanner will communicate with and that scans will be imported into.

	Compliance with all local conditions of implementation of IT-based medical devices, including information governance.
System reliability/Service continuity/Service support	Evidence of up time.
	Guaranteed response times.
	Service support offered.
	Training offered is suitable for all staff groups.
User friendliness	Operator use of software: ease of use, intuitive interface etc.
	Operator use of hardware: ease of controlling scanner in room in light and dark, setting patients up etc.
Additional equipment (as required)	Laser system and its integration with the scanner.
	Flat couch top: to index with current system, minimal SNR loss through couch, weight of the couch and range of patient sizes that can be scanned on it.
	Coil bridge solution suitable for all clinical sites of interest.
	Appropriate immobilisation devices suitable for all clinical sites to be scanned.
	Range of coils available and optimisation of these for RT.
	Image review solution simple to use with post processing available offline.
	QA and calibration hardware and associated software.
Research and development (if required)	Development and future road map in line with department needs.
	Opportunities for collaboration.
	Access to users groups or wider network of users that will add value to service.

Table 3. Primary criteria and sub-criteria for consideration when developing an MR-sim specification.

3.5 Shortlist MR scanners likely to meet the MR-sim specification

The scanner evaluation team should assess available information to determine vendor models that are most likely to meet the MR-sim specification. This information can come in the form of published literature, vendor literature or recommendations and discussions with other users of the equipment. This assessment will allow a shortlist to be produced of potential vendor models that can be fully assessed against the MR-sim specification.

3.6 Quantitative evaluation – scoring matrix

An objective method is required to compare the shortlisted MR-sims. The method followed is the same as for any large medical equipment purchase and institutions should have policies in place for this. A recommended method is to produce a quantitative scoring matrix which lists required or desirable parameters based on the specific details in the MR-sim specification. Each of these details can be given a score which can be combined to give a total weighted score for that MR-sim.

3.7 Assessing shortlisted MR-sims and making recommendations

The scoring matrix should be used to assess shortlisted MR-sims against the MR-sim specification. The assessment can be performed by assessing publicly available evidence, such as in peer reviewed literature and manufacturer's promotional material, inviting vendors to respond to the MR-sim specification (preferably in both a written and local presentation format) and performing site visits with vendors. Due to the time-consuming nature of site visits, it is recommended that the shortlist of MR-sim models is reduced to two or three before this stage. Site visits should be to somewhere that uses the same equipment in the same way that you are intending to use it. In general, site visits are performed by a subset of the scanner evaluation team. It is important that the site visit team has a good range of background disciplines and that they are briefed on the objectives of the visit and any specific knowledge required. The final scoring matrix documents can then be filled in and used as an objective way of recommending the most appropriate technology to the project board.

Section 4 MR safety for RT planning scans

Key messages of section:

- *The principles of MR safety are very different to those for ionising radiation safety, due to the different nature of the hazards.*
- *The framework for MR safety should be unified across the institution, with consistent processes and practices.*
- *Advice should be sought from a clinical scientist (MR) when implementing an MRI scanning service for RT planning. If this advice isn't available locally, then it should be obtained elsewhere - see Section 5.2.*

4.1 Introduction

The potential hazards associated with an MR scanner are very different to the ionising radiation hazards that are the main concern of most staff working in RT departments. For instance, the superconducting magnet that is a feature of most MR scanners represents a constant hazard that is present even when the scanner is off. Accidents involving such magnets can lead to sudden death if safety procedures are not followed.

Those who have experience of working in MRI for general radiological purposes will be familiar with the hazards that are present during MRI scanning for RT planning. However, some risks may be increased due to the nature of the work, including the mix of staff and the use of additional equipment.

An overview of MR-specific legislation and guidelines will be given, followed by key requirements for an MR scanning suite and advice on the safe operation of an MR scanning service for RT. The hazards of the MR scanning environment are well documented elsewhere (MHRA 2015) so they will not be described in detail.

4.2 Legislation and guidelines

The cornerstone of MR safety advice in the UK is a publication from the Medicines and Healthcare products Regulatory Agency (MHRA 2015). This document should be considered essential reading. While it does include references to legislation, other relevant legislation arises from time to time, such as The Control of Electromagnetic Fields at Work Regulations 2016.

A policy statement (IPEM 2013) has been published to describe the role of the MR Safety Expert (MRSE, see Section 4.3.1 for definition). The Society and College of Radiographers (SCoR) has produced a guidance document which sets out the professional responsibilities , the required knowledge with practical safety guidance about MR safety that is aimed at radiographers (SCoR 2019).

4.3 Key requirements for any MRI scanning suite

4.3.1 Access control and personnel

The MR Environment is a volume that fully contains the MRI hazards, including where the static magnetic field exceeds 0.5 mT. Access to the MR Environment is restricted by defining an MR Controlled Access Area (MRCAA) to which only MR Authorised Personnel have free access. The MRCAA is often larger than the MR Environment, including other parts of the MR suite. Unauthorised staff and patients must be supervised when inside the MRCAA.

The MHRA define three sub-classes of MRI Authorised Person. An Authorised Person (Non-MR Environment) has free access to the MRCAA, but not the MR Environment. An Authorised Person (MR Environment) may additionally enter the MR Environment. An Authorised Person (Supervisor) has free access to the MR Environment, is able to perform safety screening and can supervise the safety of

others in the MR Environment. MR Operators are MR Authorised Personnel who are also entitled to operate the MRI equipment.

An MR Responsible Person oversees the safety of the MRCAA and formally approves the certification of staff as MR Authorised Personnel. They should be able to consult an MRSE, usually a clinical scientist (MR), who has advanced knowledge of MR equipment, techniques and safety. At the time of writing, IPEM is developing a certification scheme for MRSEs (see Section 4.2).

Safety signs must be affixed at the entrances to the MRCAA and MR Environment to warn of the MR hazards. Designs are available from IPEM (IPEM MR-SIG Working Party 2017). Illuminated signs are not appropriate for MR scanners whose static magnetic field is not dependent on the electricity supply.

The screening of unauthorised (unclassified) staff, visitors and patients must only be carried out by an MR Authorised Person (Supervisor). The screening process should involve a visual and verbal inspection, as well as a written (or electronic) safety questionnaire. Any person being scanned should be changed into hospital gown or scrubs to avoid projectile and heating hazards arising from their own clothing.

4.3.2 Environmental control and cryogens

The safe and reliable operation of an MR scanner requires control of air temperature and humidity in the scan room and equipment room. Control of temperature and humidity in the scan room is important to allow the patient to remain at a comfortable and safe temperature and to reduce the risk of static discharges. The acceptable temperature and humidity limits will be provided by the scanner manufacturer.

Should a magnet quench occur, a large quantity of helium gas will be released, which must be channelled to the external atmosphere though a quench pipe. The pipe and its vent must be carefully designed to be compliant with The Pressure Systems Safety Regulations 2000. Since there is a possibility of leakage of helium into the scan room, the room must be equipped with an oxygen sensor to detect the depletion of oxygen. If the oxygen level drops below a specified level an alarm must sound and an emergency extractor fan must start. There is typically also a passive overpressure relief built into the scan room.

4.3.3 Documentation

The Local Rules describe the safety framework within which work should be carried out for an MRCAA or a collection of MRCAAs. They contain procedures, work instructions, equipment information and emergency instructions. A copy of the Local Rules should be available in every MR control room.

Other documentation that will be required to comply with MHRA guidance (MHRA 2015) includes:

- Logs of staff training.
- A list of Authorised Persons.
- Risk assessments.
- Service records and fault reports.
- Work instructions for particular examinations.

4.3.4 Equipment

All items that might be taken into the MR Environment must be assessed for the hazards that they might pose. MR safety assessment is a skilled process and should be carried out by an MR Authorised Person (Supervisor). To avoid the need for future assessment, items can be labelled as MR Safe, MR Unsafe or MR Conditional (STM International 2013, Shellock *et al* 2009).

It may be that some items that must be brought into the MR Environment cannot be labelled with MR safety labels. With medical equipment, this might be for workflow or infection control reasons. Such equipment should be documented to allow staff to identify which equipment can be used in the MR Environment and what safety precautions are needed.

4.3.5 Acceptance testing and safety auditing

A new MR scanner installation must be checked to ensure that it meets the safety requirements and hazards posed by magnetic fields and cryogens are adequately controlled. These checks form a part of the acceptance testing of the scanner installation.

Safety audits should be carried out annually, to ensure that safety is not compromised by degradation of mechanical or electrical parts or by other changes and that safety-related documentation is present and up to date.

4.4 Special considerations for RT planning scans

4.4.1 Staffing

RT planning scans may be carried out on a scanner that is organisationally or physically outside a radiology department. Where there is a dedicated scanner for RT planning scans, this may be located within a RT department at some distance from other MR scanners. Physical or organisational separation potentially results in increased risks, particularly in an emergency.

MR hazards may be unfamiliar to RT staff and, consequently, poorly understood. Those who work in RT are used to a situation where ionising radiation hazards are usually only present temporarily, for instance during linear accelerator 'beam-on' time. Conversely, the static magnetic field of a super conducting MR scanner is constantly present, even when the power supply is completely removed.

In many cases, MRI for RT planning scans will be undertaken by a team including therapeutic radiographers, who will contribute their expertise in setting up the patient, and diagnostic radiographers, who will operate the scanner (Speight *et al* 2019). When there are radiographers from different disciplines who meet only occasionally when performing RT planning scans, formal procedures and work instructions become more important to ensuring safe working practices.

The following specific advice is given:

- An MR scanner located separately from a radiology department must come under the same, or an equivalent, safety management structure, including the MHRA classification of personnel and local rules. Efforts should be made to propagate the MR safety culture from the radiology department to the RT MR scanner.
- When patients are being scanned, there must be at least two staff present who are classified as MR Authorised Persons. At least one must be an MR Authorised Person (Supervisor). Another must be classified as an MR Authorised Person (MR Environment), as a minimum.
- Staff operating the MR scanner while scanning a patient must be able to concentrate on their work during the whole examination.
- Staff, such as therapeutic radiographers, who set up the patient must receive MR safety training – see Section 5.3. Staff who frequently enter the MR Environment should be classified as MR Authorised Personnel.
- The responsibilities of different staff groups must be clearly defined. For instance, it must be completely clear who has the responsibility for screening the patient before they enter the MR Environment.

- The MR safety classification of staff must be apparent visibly or available as a list for MR Authorised Personnel to consult.

4.4.2 Equipment

Scans acquired for RT planning often require the use of extra equipment that is not used when performing diagnostic scanning (see Section 2.3). It is essential that the equipment is thoroughly checked (see Section 4.3.4) and labelled to ensure that it does not present a hazard in the MR Environment.

Standard MR safety checks on equipment include checks for ferromagnetism and electrical conductivity. However, other hazards should also be considered:

- Thermal insulation: Does the device significantly reduce the ability of the patient to lose heat to the environment? If so, it is important to consider how to manage heating caused by high specific absorption rate (SAR) MRI sequences.
- Mechanical: Could the device increase the risk of a crushing or laceration injury? Where devices are attached to the moving couch, they may trap parts of the patient's anatomy as the couch moves into the scanner bore.
- Evacuation: Does the device hinder evacuation of the patient in an emergency? This is highly likely in the case of immobilisation equipment. Other equipment, such as floor-mounted lasers, may obstruct the movement of an emergency evacuation couch. Evacuation training for staff must include how to deal with this extra equipment.
- Communication: Does the device make it more difficult for the patient to hear, speak or operate the emergency call switch? For instance, RT immobilisation devices, such as head shells and vacuum bags can interfere with the use of headphones that are used for communication. If the patient's speech is hindered by a device, the patient should be taught a hand gesture to indicate that they are okay. As well as hindering speech, RT head shells can cause breathing difficulties, particularly if the patient becomes unwell or vomits. The emergency call switch should be tested before each examination.

Specific items that are common in RT departments that may pose a serious hazard in an MRI Environment include positioning aids made from carbon fibre, vacuum bag pumps, metal rulers and scissors.

Section 5 Training and education

Key messages of section:

- *The use of MRI in RT requires enhanced knowledge, skills and competence for all professional groups.*
- *The knowledge, skills and competence that an individual requires depend on the tasks within the MRI in RT pathway that they are required to undertake.*
- *Three models of MRI for RT use are given. For each model, role-specific training requirements are recommended.*

5.1 Introduction

The use of MRI in RT is a relatively new practice in the UK and there are currently no minimum educational requirements for persons using MRI for RT planning or treatment (Westbrook 2017, Eccles *et al* 2017). The lack of national guidance in MRI training in the RT community has been identified for all staff groups (Eccles *et al* 2017, Speight *et al* 2019). As a result of this, the recommendations in this section have been developed for all staff groups and the Society and the College of Radiographers (SCoR) have published an overview of the educational requirements for therapeutic radiographers when using MRI in RT (SCoR 2020) which should be followed for all radiographer training. Until these recommendations are taken up by formal training schemes, training will be performed primarily 'in-house', so it is essential for there to be a close working relationship between radiology and RT staff (Rai *et al* 2017). At the time of writing the HCPC and SCoR are both reviewing standards of proficiency and professional guidance respectively with updated frameworks for training and education expected and should be followed when available.

Supplementary education is required for all staff groups to ensure the safe and effective use of MRI in RT. The education requirements for each individual are dependent on what tasks they will undertake in the process. The education required is also dependent on the model of access to MRI for RT planning, which broadly fits into one of three categories:

1. MRI acquired in a diagnostic position by diagnostic radiographers only (typically only used for brain patients).
2. MRI acquired in an RT position, by diagnostic and/or therapeutic radiographers, on a non-MR-sim scanner.

3. MRI acquired in an RT position, by diagnostic and/or therapeutic radiographers, on an MR-sim (or an MR-linac).

Core to all training is safety. The fundamental message being that, starting from the point of referral, everyone is responsible for MR safety. All staff must be able to work safely and effectively within their scope of practice and within the legal and ethical boundaries or their profession.

Recommended educational requirements, and how this can be delivered, for each staff group are given in Tables 4, 5 and 6 for the three different models of MRI in RT. It is important to note that the educational recommendations are in addition to what would be expected conventionally for that discipline, i.e. it is assumed that diagnostic radiographers already have relevant knowledge in MRI physics, MR safety and MR image interpretation and therapeutic radiographers have relevant knowledge in RT set-up and RT planning requirements.

As there is currently no formal mandatory training in the UK it is strongly recommended that all training is well documented electronically, as evidence, and assessed at appropriate points to ensure understanding, as is good practice for all training in RT and radiology disciplines. Training record maintenance in each centre is the responsibility of the MR Responsible Person (see Section 4.3.1).

5.2 Support from clinical scientists (MR)

RT departments in institutions that do not employ clinical scientists (MR) should consider seeking the services of other institutions within the same region. It may be possible to extend MRI services provided for acceptance testing, site planning and QA into the development of MRI protocols for RT planning. If local institutions cannot provide this service, the IPEM MR special interest group can be contacted for advice in locating a suitable service provider. Centres with an MR-linac would also benefit from this support.

5.3 Recommended training requirements

Table 4 suggests the educational requirements for staff when MRI is acquired in the diagnostic position by diagnostic radiographers without the assistance of therapeutic radiographers. Table 5 gives the additional training requirements for the case when MRI is acquired in the RT position, by diagnostic and/or therapeutic radiographers. Table 6 details the further training required when MRI is acquired

on an MR-sim. Note that the tables are cumulative: the training detailed in Table 4 is required for all three cases and acquisitions on an MR-sim require the training detailed in all three tables.

Staff group	Training required	Potential method of training delivery
All who enter the MRCAA	• MR safety knowledge - basic awareness of environmental and physiologic hazards to themselves and others • Understanding the local MRI access policy (i.e. local rules (Section 4.3.2)) • Understanding of professional scopes of practice (Section 4.2) • It is recommended that MR safety knowledge is refreshed annually	Delivered locally, using the same method as for radiology staff, but typically by a clinical scientist (MR). Online material such as the e-Learning for Healthcare MRI safety course.
Diagnostic radiographers	• Basic RT knowledge including RT imaging requirements and how they differ from diagnostic imaging (Section 2.1) • Awareness of the importance of not changing parameters and the implications of doing so	Delivered locally by clinical scientist (RT) or therapeutic radiographers.
Staff optimising MRI sequences for RT	• More advanced RT knowledge than provided to diagnostic radiographers • Understanding of implications of manipulation of MRI parameters on RT pathway (see Sections 7.3 and 7.4)	Delivered locally by clinical scientists (RT/MR).
Operators of image registration	• How to perform registration, implications of any errors and how to assess registration quality • Understanding of MRI anatomy, including appearance of targets and organs at risk (OAR) on multi-parametric MRI • Awareness of anatomical priorities	Local hands-on sessions by clinical scientists (RT/MR) and clinical oncologist/radiologist with suitable MRI anatomical knowledge. Online material such as the e-Learning for Healthcare Image Interpretation course.
Anyone who will contour on the MRI	• Implications of any error in the registration process and how to assess registration quality • Understanding of MRI anatomy, including appearance of targets and OAR on multi-parametric MRI • Knowledge about MR image contrasts/sequences available to request optimal imaging for patients	Local hands on sessions by clinical scientists (RT/MR), radiologists or specialized radiographers and reading the literature. Online material such as the e-Learning for Healthcare Image Interpretation course.
Anyone consenting or referring a patient	• Basic MR safety knowledge as per all who enter MRI suite • Awareness of safety implications of MRI scanning patients - the referrer should be the first check point for ensuring the use of MRI is safe and appropriate for each patient • The benefit of MRI for patients, allowing a risk benefit analysis of the MRI scan to be done on a per patient basis	Delivered locally by appropriately qualified/educated/authorised individuals

Table 4. Training requirements for MRI acquired in a diagnostic position by diagnostic radiographers only.

Staff group	Training required	Potential method of training delivery
Diagnostic radiographers	RT knowledge including: • Patient set-up/immobilisation • Preparation (bladder-filling, etc.) (Section 6) • Planning requirements (Section 2)	Delivered locally by clinical scientists (RT) or therapeutic radiographers or external courses.
Therapeutic radiographers	• Basic MRI physics knowledge including MRI hardware, image acquisition types and different contrasts available • Advanced MR safety knowledge including legislation (Section 4.2) • Awareness of patient set-up/immobilisation and limitations of positioning within an MR Environment with respect to safety and reproducibility of position (Section 6)	Delivered locally, using the same method as for radiology staff, but typically by a clinical scientist (MR). Delivered locally by clinical scientist (RT) or external courses.
Clinical scientists (RT/MR) involved in commissioning and providing routine support for the service	• Advanced MR safety and physics • Understanding of the whole patient pathway • Awareness of implications of changing acquisition parameters on registration and contouring accuracy and QA requirements (Section 8)	Delivered locally, using the same method as for radiology staff, but typically by a clinical scientist (MR). Delivered locally by clinical scientist (RT) or external courses.

Table 5. Training requirements for MRI acquired in a RT position, by diagnostic and/or therapeutic radiographers, on a non-MR-sim. NB these are the extra training requirements for this model in addition to those shown in Table 4.

Staff group	Training required	Potential method of training delivery
Therapeutic radiographers working on an MR-sim	The aim is to up-skill to the level they can work in close cooperation with diagnostic radiographers. Training should include: • Sufficient MR safety knowledge and experience to carry out safety screening checks and supervise patients in the MR Environment according to their MHRA Authorised Person level • Advanced MRI physics knowledge to understand impact of changing imaging parameters • Experience in MR-sim platform use, to the level where they could competently scan patients if this was the workflow decided upon in your centre • Knowledge of local QA procedures • Advanced understanding of and familiarisation with MRI anatomy, including appearance of targets and OAR on multi-parametric MRI	Delivered locally, using the same method as for radiology staff, but typically by a clinical scientist (MR) and/or diagnostic radiographer. Delivered locally by clinical scientist (RT) or external courses /vendor training. Online material such as the e-Learning for Healthcare Image Interpretation course. NB once local expertise has been achieved then in-house training can occur. MRI experience can be achieved via secondments in local radiology departments.
Diagnostic radiographers working on an MR-sim	The aim is to up-skill to the level they can work in close cooperation with therapeutic radiographers. Training should include: • Sufficient knowledge of the whole patient pathway to enable accurate patient set-up with or without lasers/immobilisation devices • Experience in MR-sim platform use to the level where they can competently scan patients • Knowledge of local QA procedures	Delivered locally by clinical scientist (RT), therapeutic radiographers or external courses/vendor training. RT experience can be achieved via secondments to CT simulators locally.
Clinical scientists (RT/MR) involved in commissioning service	• Experience in MR-sim platform • Understanding of QA requirements to set up local QA procedures (Section 8)	Delivered locally, using the same method as for radiology staff, but typically by a clinical scientist (MR). Delivered locally by clinical scientist (RT) or external courses /vendor training.

Staff responsible for safety for MR-sim	• Advanced RT knowledge to fulfil the requirements to set up safety framework on MR-sim specifically related to MRI in RT • Understanding of QA requirements to set up local QA procedure (if responsible for this)	Delivered locally, using the same method as for radiology staff, but typically by a clinical scientist (MR). Delivered locally by clinical scientist (RT) or external courses.
RT engineers	• Knowledge of IT requirements of system and auxiliary equipment • Basic MRI physics and safety knowledge regarding equipment and tool use in suite and scan room	Delivered locally, using the same method as for radiology staff, but typically by a clinical scientist (MR). External courses /vendor training.

Table 6. Training requirements for MRI acquired in an RT position, by diagnostic and/or therapeutic radiographers, on an MR-sim. NB these are the extra training requirements for this model in addition to those shown in Table 4 and Table 5.

Section 6 Patient set-up for MRI simulation

Key messages of section:

- *Imaging in the treatment position both externally (immobilisation) and internally (e.g. reproducible bladder/bowel preparation) should be performed whenever possible to aid MRI-CT registration.*
- *Coil supports or bridges should be used where appropriate to ensure that the MRI coil does not distort the external patient contour.*
- *The tumour region should be positioned as close to the MRI isocentre as possible to minimise geometric distortion.*
- *External lasers can be useful but are not essential for most applications where MRI-CT registration will be employed.*

6.1 General considerations for patient set-up for MRI simulation

The following aspects should be considered for patient set-up for an MRI where the image will be registered with CT:

- A flat couch top is essential for extra-cranial scans to reproduce the posture and internal anatomy of the patient and achieve adequate RIR accuracy between the planning CT and MRI.

- Coil supports or bridges should be used, where appropriate, to avoid compression of the patient contour by the weight of the coils. The coil support should be positioned as close as possible to the skin to maximise the signal.
- The standard patient position used at CT simulation must be reproduced as closely as possible.
- Any bladder and bowel preparation used at CT simulation should also be followed for the MRI simulation. It may be necessary to adapt the timing delay to reflect the longer acquisition times for MRI.
- Lasers are very useful, but not essential (Paulson *et al* 2016). If the planning CT has been acquired prior to the MRI, then lasers can be used to align the patient's tattoos to improve the reproducibility of the patient set-up on MRI. If the MRI is acquired first, then the lasers can be used to place the skin marks on the patient to improve the set-up consistency with the planning CT.

- Immobilisation devices must be checked for safety (see Section 4.3.4). MR Safe lock-bars are commercially available to enable the indexing of immobilisation devices for reproducible patient set-up. Other commercially available MR Safe or MR Conditional immobilisation solutions are available and should be considered, as devices manufactured for CT imaging and RT treatment may not be safe to use.

- If RT set-up tattoos are used, it is best practice to check the manufacturer's specification to establish whether there are any electrically conductive constituents as, in theory, this could cause local heating or burns to the patient.

This advice is also relevant to imaging with an MR-linac, where the MRI is fused with a CT scan.

6.2 Immobilisation devices

For extra-cranial sites, it is highly desirable for the patient position and immobilisation device used for CT simulation to be reproduced on the MR-sim. However, this may not always be possible due to the smaller internal bore of the MR scanner and the materials used in standard immobilisation devices, which may not be MR Safe or MR Conditional. For intra-cranial sites, reproducing the RT planning position may not be as critical (see Section 9.3.1).

Commercially available immobilisation equipment that is appropriate for MRI may be cost prohibitive so a compromise may need to be made regarding alternative solutions. This can be achieved by

reproducing the patient position as closely as possible using MR Safe supports and cushions. This may require modification of the standard CT simulation patient position or in-house production of a device which replicates the required patient position, manufactured from MR Safe materials. Any alteration in patient positioning on MRI from the standard CT simulation should be discussed with clinical oncologists, therapeutic radiographers and clinical scientists (RT) to assess for any impact on RT dose delivery and reproducibility.

The use of conductive materials in the construction of an immobilisation device may cause signal loss and should be avoided where possible; carbon fibre is an example (Jafar *et al* 2016). A large SNR drop, such as shown in Figure 1, is unusual and indicates a risk of heating of the device by induced currents.

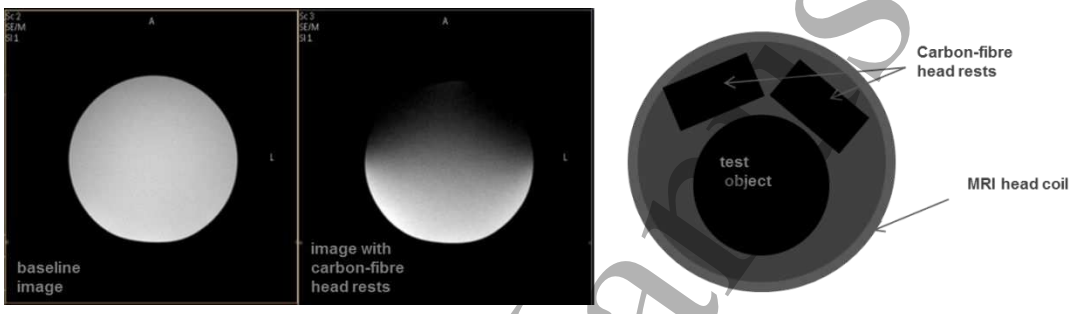


Figure 1. Carbon fibre device (head rest) placed above test object causing reduction of SNR (centre), when compared to baseline image without head rest (left). This suggests a conductive material, causing B_1 inhomogeneity. Schematic of the phantom set-up is shown on the right.

6.3 Preventing RF burns

Appropriate care needs to be taken to prevent RF burns caused by current induction from skin-to-skin contact or proximity to the bore, or loops in coil cables. It is recommended that foam pads of sufficient thickness should be used as insulation (MHRA 2015), but care must be taken to ensure this doesn't alter the patient position or external contour and further advice can be sought in the MR scanner manufacturer's recommendations or from a MRSE.

6.4 Flat couch top

When using a flat couch top, consideration must be given to the fact that the additional thickness moves the patient further away from the posterior coils in the couch which could have a detrimental effect on image quality. A couch top that is compatible with RT departmental equipment and can allow

RT specific equipment to be indexed in the same way is an advantage, although identical indexing is not always achievable due to variations in the positioning requirements on the couch.

6.5 Use of lasers – indexing and reproducibility

Use of external RT set-up lasers to align patients is desirable but may not be essential for MRI-CT image registration pathways. RT lasers are particularly helpful for patient set-up in MRI following CT simulation, as the set-up marks applied in CT can be used to replicate patient posture and rotation. If RT lasers are not available, the internal MR scanner lasers can be used, providing they have QA checks performed. Indexing and/or measurements from tattoos could aid in reproducible set-ups. Also, using locally agreed anatomical landmarks improves patient set-up. For example, line between supra-sternal notch and xiphisternum for head and neck and thorax patients or between xiphisternum and symphysis pubis for pelvis patients. If using lasers, it is essential that the power supply to them is switched off during acquisition, otherwise interference artefacts can be produced.

6.6 Documentation of set-up

It is essential that details of the patient set-up are recorded according to standard RT protocols. Electronic transfer of set-up details would be ideal. A 'set-up transfer' sheet (paper or electronic) could be employed across all pre-treatment imaging (i.e. CT and MRI simulation) to inform other departments of immobilisation requirements and any special instructions, e.g. bladder filling requirements. The production of a local 'MRI for RT guidelines' booklet to cover local MRI protocols and patient set-up can aid in consistency and is recommended.

6.7 Treatment site-specific guidance

6.7.1 Brain

For non-stereotactic radiosurgery (non-SRS) tumour sites contained within the skull, the standard MRI head coil can be used to achieve optimal image quality rather than attempt to acquire the MRI image in the immobilised RT position. SRS brain treatments require a higher degree of geometric accuracy and acquisition of MR images in the SRS immobilisation device could be considered, although acquisition in the standard MRI head coil is acceptable, as long as the quality of the image registration to CT is adequately scrutinised. If acquiring in the treatment position and the SRS immobilisation

device is not MR Safe or MR Conditional, then an additional device which reproduces the head position could be purchased or manufactured in-house from MR Safe/conditional materials.

6.7.2 Head and neck

It is recommended that the patient is scanned in their treatment mask to improve MRI-CT image registration. If the treatment mask is rigid, MRI coils can be positioned directly onto the mask, otherwise a coil support or bridge should be employed. When scanning a patient in the treatment mask, ear plugs should be used to protect the patient's hearing. Imaging the complete patient contour including the shoulders is desirable, but this may require increasing the voxel size or accepting a prolonged scan time. A smaller FOV covering only the central region of the head and neck may be considered, to achieve adequate image quality in an acceptable scan time. An example image of a patient set-up for a head and neck patient can be seen in Figure 2.

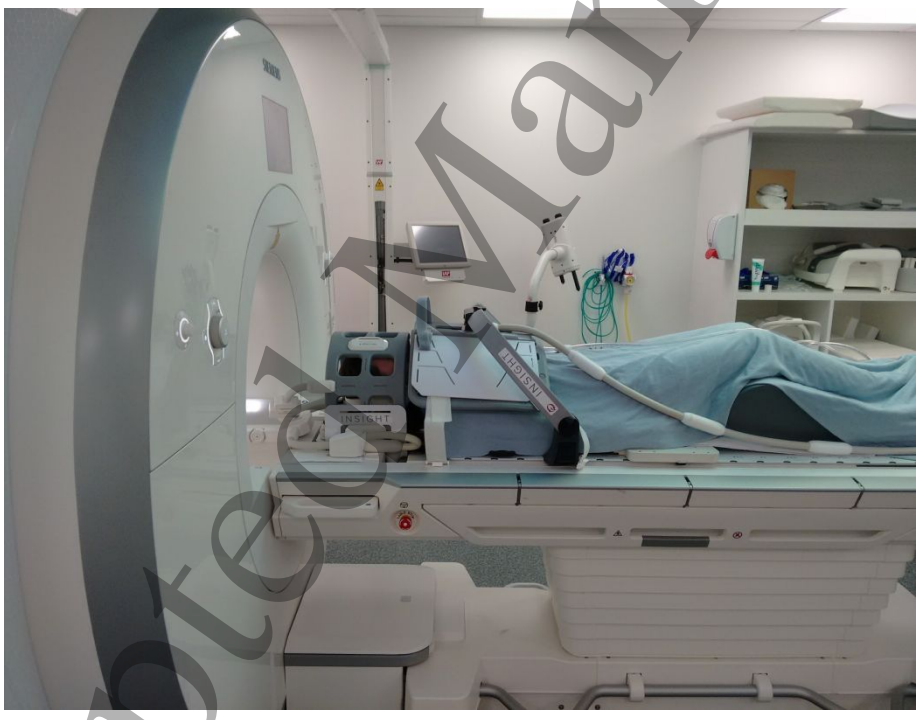


Figure 2. Example of a head and neck MRI patient set-up.

6.7.3 Pelvis

Replicating knee and ankle supports used in CT simulation is recommended. In addition to a flat couch top and coil supports, reproducing the position of the legs is also important as, if the knees are bent in the MRI but straight in the CT, the difference in pelvic rotations means the internal anatomy is

difficult to register. Care should be taken when securing the coil to the support and moving the cables to the appropriate socket to make sure that the patient does not move. Bladder filling during the imaging session is more significant than in CT, particularly if more than one sequence is used. This can be compensated for by timing the standard imaging delay to half-way through the MR imaging session. An example image of a patient set-up for a pelvis patient can be seen in Figure 3.

Figure 3. Example of a pelvis MRI patient set-up.

6.7.4 Abdomen/thorax

Immobilisation for abdominal/thoracic RT varies between departments but, whether it is achieved using an vacuum bag or a wing board indexed to a flat top couch, the immobilisation used in CT should be replicated in MRI where possible. To reduce breathing motion, scans can be acquired in breath-hold. However, abdominal compression can also reduce motion and MR Safe or MR Conditional compression devices are commercially available. Coil supports/bridges should be employed and, depending on the design of the support, care must be taken to ensure that the vacuum bag, abdominal compression and coil supports can all be indexed. For thoracic scanning, enough coils are required to cover the thorax, lung apices and brachial plexus. Example images of a patient set-up for an abdominal/thoracic patient can be seen in Figure 4.

Figure 4. Examples of a thoracic (top) and an abdominal (bottom) MRI patient set-up.

6.7.5 Spine

For MRI set-up purposes, spine patients can be considered to be one of two groups, upper and lower spine, in the same way that they are for CT simulation and treatment. For the upper spine group, it is recommended that patient set-up is similar to that for head and neck patients (see Section 6.7.2). The difference being that the coils will be placed more inferiorly than for a head and neck patient, so as to be anterior to the vertebrae to be treated. The coils can be placed on the mask if it covers this region

or on a coil bridge/support if the region to be scanned is inferior to the mask. For the lower spine group the recommended patient set-up is very similar to that for abdominal patients (see Section 6.7.4) except that anterior coils are generally not required if enough signal if produced from the coils in built into the bed and will mimic the local set-up on the CT simulator for these patients.

Section 7 Sequences for MRI for RT planning

Key messages of section:

- *The purpose of diagnostic MRI and MRI for RT planning is different, as are the sequence requirements.*
- *MRI sequence optimisation involves a trade-off between properties including SNR, resolution, time, contrast and geometric distortion.*
- *A clinical scientist (MR), radiologist and/or diagnostic radiographer specialising in MRI can assist with the development of robust sequences that exhibit desirable soft tissue contrast with minimal distortion.*
- *Care should be taken not to modify sequences once they are optimised, in order to maintain consistency.*
- *Summary tables providing example sequence requirements for various tumour sites are provided to promote consistency and to offer a starting point for centres implementing MRI for RT planning.*

7.1 Introduction

The purpose of MRI for RT is to provide confidence in the localisation of target and OAR structures for RT planning. Therefore, the choice of MRI sequence and the required sequence optimisation for MRI for RT differs from the diagnostic case. MRI sequence optimisation comprises a trade-off between SNR, resolution, contrast, acquisition time, geometric distortion and image artefacts. For each change, one needs to consider whether, for example, the spatial resolution is sufficient for delineation, the scan time is tolerable for the patient and the distortion does not significantly affect planning. This section describes MRI for RT sequence requirements in order to promote consistency, as well as to offer a starting point for sites that are developing MRI for RT at their institutions. Although MR-linacs have been released with pre-set sequences, the same principles discussed in this section should be observed.

7.2 General sequence optimisation

It is advisable to involve a clinical scientist (MR), radiologist and/or diagnostic radiographer when optimising sequences for MRI for RT planning, due to the different requirements between MR imaging for diagnostic and RT purposes. Input is also required from a clinical scientist (RT) to determine image requirements, e.g. slice thickness and orientation for registration and contouring (see Section 2.1). In addition, clinical oncologists may not be familiar with the variety of soft-tissue contrast techniques MRI has to offer as well as potential artefacts from these sequences and so should be supported in MRI image interpretation for contouring by a radiologist when required.

MRI takes longer to acquire than CT and long periods of immobilisation may result in patient discomfort and reduced compliance that could lead to motion artefacts or incomplete data acquisition. Therefore, sequences should be kept as short as possible to obtain the required image quality and the most important sequences should be prioritised at the start of the scanning protocol. MRI for RT may be acquired using different receive coils to diagnostic scans (to accommodate for immobilisation devices) and this must be considered during sequence optimisation. Using different coils may affect SNR and anatomical coverage. In addition, coil uniformity correction filters should be enabled to provide uniform signal intensity across the image, especially when using surface coils.

While MR has the ability to acquire images in any orientation, the decision on the orientation of the imaging volume depends not only on the ability to visualise the anatomy, but also the ability to outline the volume in combined MR-CT datasets. The introduction of interpolation artefacts when CT and MR images are registered is an important issue that requires consideration when MR is acquired in an orientation different to that of the CT image; this is of particular concern in MR datasets with low in-plane or slice resolution. Other key acquisition parameters are discussed in Table 8.

Gadolinium-based contrast agents may be used to highlight the gross tumour volume (GTV) and surrounding structures, e.g. OARs or vessels. The decision on whether to use contrast agent for a particular tumour site should follow discussion with a radiologist and a risk-benefit analysis, due to the safety implications. Repeated use of gadolinium contrast over short time scales (generally less than 7 days) is not advised (RCR 2019).

7.3 **Geometric distortion**

MRI geometric distortion can be scanner-related or patient-induced and is generally a combination of both. Scanner-related distortion is minimised by careful design of the scanner hardware and by automatic post-processing of the acquired data, known as distortion correction. This distortion is minimal close to the centre of the magnet (the isocentre) and increases rapidly when moving away from the isocentre. Manufacturer-supplied automatic gradient non-linearity distortion correction should be enabled for all MRI sequences for RT. As a minimum, 2D distortion correction should be applied and 3D distortion correction is recommended where available.

Patient-related distortion arises from variations in the resonant frequency of protons, either due to their chemical environment (in fat or water, for instance) or the distribution of materials of differing magnetic susceptibility (air, body tissues, metallic implants) in space. The former effect leads to what is known as a chemical-shift artefact, where signals from different tissues are displaced from one another. The latter leads to susceptibility-related distortion of the image, due to inhomogeneity in the static magnetic field. Both chemical-shift and susceptibility effects are larger at higher magnetic fields. Sequences vary in their susceptibility to patient-related distortion and must be optimised to minimise it. Measures to reduce the extent of signal loss and distortion attributed to local field inhomogeneities and susceptibility differences include the use of spin echo (SE) sequences over gradient echo (GE) sequences, increasing receiver bandwidth and reducing echo time (TE) (Hargreaves *et al* 2011, Port and Pomper 2000). Care should be taken to ensure that SNR, resolution and contrast remain sufficient when making such changes. Metal artefact reduction sequences can be employed when scanning tumour sites that are affected by artefacts from metallic implants, such as a hip prostheses (Pathmanathan *et al* 2019, Koch *et al* 2009, 2011, Schmidt *et al* 2016). Susceptibility artifacts are more pronounced at higher fields, and in some cases it may be disadvantageous to perform MRI for RT planning at higher fields despite the advantages of higher SNR.

Displacements associated with chemical shift and field inhomogeneity occur along the frequency encoding (readout) direction. The main contributing factor is the amplitude of the readout gradient, determined by the operator's choice of readout bandwidth; it is known that many diagnostic pulse sequences do not produce geometrically accurate images due to the use of low receiver bandwidth. However, any increase in receiver bandwidth is associated with a rise in noise levels, which must be taken into account.

Susceptibility-induced field inhomogeneity due to the patient can be measured directly, using a magnetic field (B_0) mapping sequence provided by the main MRI manufacturers, or estimated from

literature values (further details and recommendations on when to measure or estimate values are found in section 8.6.2). The susceptibility-induced field inhomogeneity can be very localised but has been shown in the literature to be under 6 ppm for brain (even when considering metal implants), neck, lungs, thorax and pelvis (Schmidt and Payne 2015, Wang *et al* 2013, Stanescu *et al* 2012, Matakos *et al* 2017, Lundman *et al* 2017).

Sequences should be optimised such that displacements along the frequency encoding direction associated with chemical shift and susceptibility-induced field inhomogeneity are within the desired tolerance. The tolerance required is a local clinical judgment dependent on the treatment site and technique, but values of 1 mm or 2 mm are typical. The geometric displacement between fat and water (due to the chemical shift of 3.5 ppm – 225 Hz at 1.5 T and 450 Hz at 3.0 T) should be reduced by increasing the receiver bandwidth. The bandwidth is displayed differently across MR systems manufacturers and minimum bandwidths required to keep the fat water shift under 1 mm at both 1.5 T and 3.0 T are shown in Table 7. For example, for a 3 T Siemens system and a 1 mm voxel (in the readout direction) a bandwidth of 450 Hz/pixel is required to keep displacements under 1 mm for field inhomogeneity up to 3.5 ppm. If the field inhomogeneity in the volume of interest is estimated to be 7 ppm, it would be necessary to double the receiver bandwidth in proportion to achieve the same effect (900 Hz/pixel for 1 mm maximum displacement). If the field inhomogeneity is of the order of 3.5 ppm, but if displacements of 2 mm can be tolerated for the clinical service, the readout bandwidths presented on the table can be halved.

In 2D MRI sequences, the slice selection gradient is presumed to be high enough to select fat and water signals within the same slice and thus field inhomogeneity under 3.5 ppm has limited impact on slice geometry (Doran *et al* 2005). In 3D sequences the use of phase encoding in the slab selection direction is favourable to geometric accuracy, even if the slab selection gradient is lower.

Manufacturer:	**Philips**	**Siemens**		**General Electric**					
Magnetic field:	**1.5 T or 3.0 T**	**3.0 T**	**1.5 T**	**3.0 T**			**1.5 T**		
Matrix size:	-	-	-	**128**	**256**	**512**	**128**	**256**	**512**
Pixel size in readout direction (mm)	**Water-fat shift** (pix)	**BW/pix** (Hz/pix)	**BW/pix** (Hz/pix)	**± BW** (kHz)	**± BW** (kHz)	**± BW** (kHz)	**± BW** (kHz)	**± BW** (kHz)	**± BW** (kHz)
2.22	0.45	1000	500	64	128	256	32.0	64.0	128.0
2.00	0.50	900	450	58	115	230	28.8	57.6	115.2
1.67	0.60	750	375	48	96	192	24.0	48.0	96.0
1.11	0.90	500	250	32	64	128	16.0	32.0	64.0
1.00	1.00	450	225	29	58	115	14.4	28.8	57.6
0.83	1.20	375	188	24	48	96	12.0	24.0	48.0
0.67	1.50	300	150	19	38	77	9.6	19.2	38.4
0.56	1.80	250	125	16	32	64	8.0	16.0	32.0
0.50	2.00	225	113	14	29	58	7.2	14.4	28.8

Table 7. Minimum receiver bandwidth recommended for all RT sequences to keep displacement of 3.5 ppm (fat-water chemical shift) under 1 mm. Different manufacturers present bandwidth in different ways: water-fat shift, bandwidth per pixel (BW/pix) and total bandwidth (±BW).

Manufacturers often allow the user to select whether the FOV is scanned at isocentre or at some other fixed position. Magnetic field homogeneity is greatest in the region surrounding the magnet isocentre. Within this region the gradient-induced distortion is minimal and so, where possible, the volume of interest should be placed as close as possible to this location. For diagnostic imaging of the brain, the FOV is routinely positioned around the whole head (Figure 5.), although this sets the brain slightly off-isocentre. For critical cases such as SRS planning, minimal distortion will occur when the FOV is centred on the brain (not whole head) such that the brain is at magnet isocentre (Figure 5.). The same technique should apply when imaging other anatomical regions for MRI for RT planning.

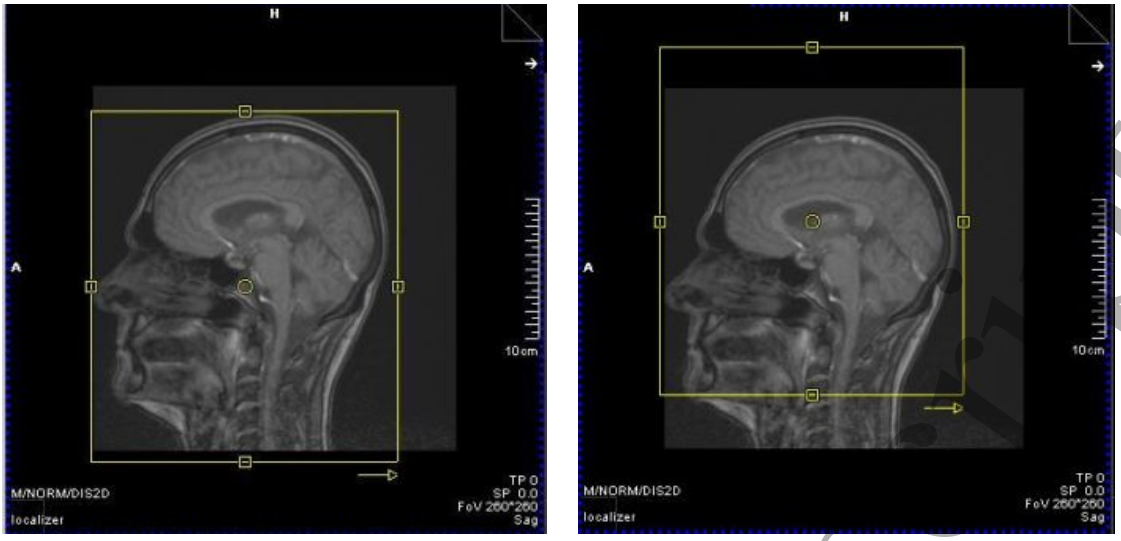


Figure 5. (Left) FOV centred over the whole head, as is routine in diagnostic imaging. This results in the brain being scanned slightly off-isocentre. (Right) The centre of the FOV (hence magnet isocentre) is positioned over the brain, when minimal distortion is required. For example, with MRI planning in SRS cases, the FOV should be centred on the brain and not the whole head, to reduce geometric distortion.

Shimming aims to improve the magnetic field homogeneity across the imaging volume. Generally, MRI systems automatically set the shim volume to be equal to the imaging FOV, though it depends on the shim mode that has been enabled. To reduce geometric distortion it is recommended to manually adjust the shim volume such that a minimal amount of external air is included in the shimming volume, position the shim volume over the volume of interest, e.g. GTV and OARs, as shown in Figure 6 for the brain, and minimise the areas of tissue not required for planning or registration, e.g. the oral cavity.

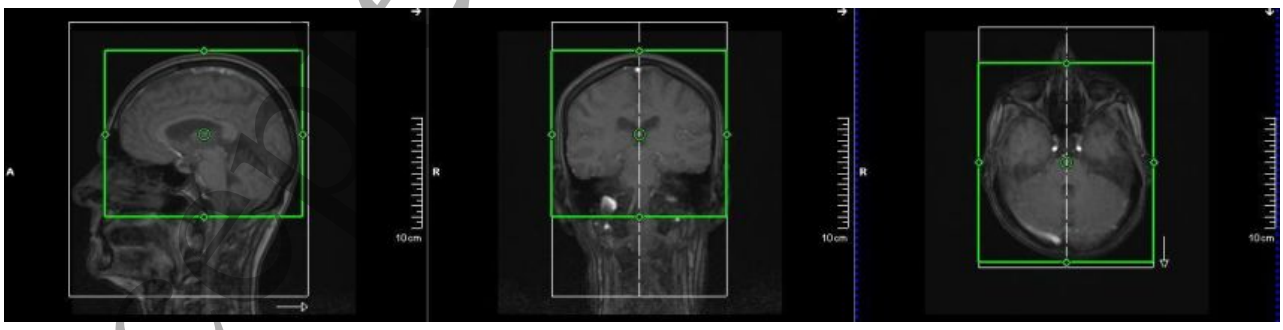


Figure 6. Shimming aims to improve magnetic field homogeneity over the imaging volume. The (green) shim box should be positioned such that the region of interest (i.e. brain) is covered and other sources of field inhomogeneity, e.g. sinuses and oral cavity, which are not important for registration are not included. Notice that the (grey) FOV imaging volume is larger in this case, to image the whole head.

7.4 **Motion management**

Motion artefacts in MRI can be related to respiration, cardiac motion, bowel motion, blood flow or voluntary or involuntary patient motion. Techniques to minimise the effects of such motion on MR images are now described.

Respiratory triggering limits acquisition to a particular part of the respiratory cycle, to minimise respiratory motion artefacts. By default, triggered sequences generally acquire data at end-exhalation, which is held for longer than end-inhalation. 3D imaging can be acquired at breath-hold with acquisition times reduced to ensure patient compliance. End-expiration breath-holds are preferable as the time-averaged tumour motion is closer to end-exhale position (Seppenwoolde *et al* 2002). 3D acquisitions with multiple averages will give a time-averaged tumour position. However, the resulting images may be of insufficient quality for treatment planning, due to motion induced blurring, and these acquisitions can take a long time.

Use of non-Cartesian acquisitions, where the centre of k-space is oversampled, can reduce motion artefacts (Pipe 1999). However, when using 2D variants of such non-Cartesian sequences (e.g. propeller k-space acquisition), coronal or sagittal reconstructions should be checked for discontinuities in the anatomy between slices. 4D MRI techniques are available (e.g. self-gated stack-of-stars, stacked 2D cine), although they generally require additional post-processing offline (Stemkens *et al* 2018). Real-time motion can be imaged using 2D cine imaging to assess the range of GTV and OAR motion. The increasing exploitation of real-time guidance on the MR-linac can be expected to further develop and benefit motion management sequences available at MRI simulation.

Saturation bands can be placed over the abdominal wall in the image to suppress respiratory artefacts, but care should be taken to ensure that the tissue suppression in the image does not degrade subsequent image registration. Switching the frequency and phase encoding directions may also prove beneficial for reducing respiratory artefacts in pelvic and abdominal examinations, as motion ghosting artefacts mainly appear in the phase-encode direction. Saturation bands outside the FOV and flow compensation can be used to suppress flow ghosting artefacts. ECG triggering can be employed to reduce cardiac motion artefacts where required. However, the combination of respiratory and cardiac triggering can prolong the acquisition time considerably.

Anti-peristaltic drugs, such as intravenous hyoscine butylbromide or glucagon, can be administered to reduce peristalsis for abdominal and pelvic MRI examinations (Masselli and Gualdi 2012).

Involuntary 'gross' patient motion can be minimised with immobilisation devices, by improving patient comfort (e.g. with cushions), administering painkillers to reduce discomfort and, where appropriate, using sedation or general anaesthetic. However, note that sedation and anaesthetics have MR safety challenges beyond the scope of these guidelines.

7.5 Sequences for MRI for RT planning – summary tables

Example options that can be changed on an MR scanner and their requirements for MRI in RT are shown in Table 8. Example sequences for MRI in RT are shown by anatomical site in Table 9. Recommendations in these tables are based on consensus opinions of the authors, a survey performed on MR in RT users (Speight *et al* 2019) and the literature (Christian Gustafsson *et al* 2016, Liney and van der Heide 2019, Schmidt and Payne 2015, Paulson *et al* 2016).

Options	MRI for RT planning requirements
Coils	Coils must be placed close to the patient, ideally not touching them, so as not to deform anatomy. Coil intensity uniformity correction should be applied on the system; this is especially important to reduce coil flare when using surface coils.
FOV position	The centre of the FOV should be positioned over the anatomy of interest, such that FOV and magnet isocentre are aligned for improved geometric fidelity.
In-plane resolution (i.e. plane to be contoured on, usually transverse, and not necessarily the plane of acquisition).	Resolution should be adequate to allow GTV and OAR contouring and should ideally be ≤ 1 mm.
Slice thickness and gap	Ideally similar to CT slice thickness, although in order to reduce acquisition time and achieve sufficient SNR slightly larger MR slices can be acquired. It is desirable to have no slice gap. Slice thickness ideally < 3 mm for most cases and < 1 mm for SRS cases.
3D vs 2D acquisition	3D acquisitions should be used to provide high resolution isotropic imaging, allowing 3D distortion correction to be enabled. The soft-tissue contrast offered by some 3D sequences may not be suitable for all anatomies.
Gradient non-linearity correction	2D distortion correction should be applied as a minimum. 3D distortion correction should be applied if available. Some systems allow 3D distortion correction to be applied to 2D multi-slice datasets.
Receiver bandwidth	Fat-water shift should be limited to one pixel or < 1 mm. Increasing bandwidth reduces distortions caused by susceptibility differences and by fat-water shifts.
Soft tissue contrast	This should be decided based on the tumour site. A variety of soft tissue contrasts may be required to highlight targets and OARs.
Contrast agent	May be used to highlight targets or OARs. The decision whether to use contrast agent should follow discussion with a radiologist.
Shim volume	The shim volume should be positioned over the region of interest, while minimising the amount of air within the volume (e.g. external body contour, bowel and sinuses). It is worth noting that shimming over a region of interest will typically increase the geometric distortion outside the region of interest (Adjeiwaah *et al* 2019).

Table 8. Examples of options and their requirements when performing MRI for RT planning.

Tumour Site	Sequences	Comments
Brain	3D T1 (GE/FSE) 3D T2 (FSE) 2D/3D T2 FLAIR (FSE) 3D T1 (GE/FSE) + contrast	T1 (pre-contrast) sequence to assist with image registration and T1 (post-contrast) for identification of GTV and metastases. T2 to assist with delineation of GTV and OARs. FLAIR for delineation of gliomas and to assist GTV and OAR delineation in cases of oedema. High resolution isotropic 3D acquisitions could be acquired in the sagittal plane to allow for as transverse reconstruction. It must be ensured that the treatment planning system can accept non-transverse or reconstructed images if required.
Head and neck	2D/3D T2 (FSE) 2D/3D T2 (FSE) + fs 2D/3D T1 (GE/FSE) + contrast + fs	T1 with contrast to highlight GTV and OARs. T2 and T2 + fs sequences to differentiate oedema and to assist GTV and OAR contouring, e.g. parotid glands. Dixon-based water-only sequences can provide images with more uniform fat suppression than spectral fat saturation techniques.
Spine	3D T1 (GE/FSE) 3D T2 (FSE)	High resolution isotropic 3D acquisitions could be acquired in the sagittal plane to allow for transverse reconstruction.
Prostate	2D/3D T2 (FSE)	T2 sequence highlights prostate, GTV and OARs. Prostate cancer is generally seen as hypo-intense compared with surrounding normal prostatic tissue. T2* sequences can be used to better visualise fiducial markers.
Cervix	2D/3D T2 (FSE)	T2 sequences are suitable for distinguishing GTV and surrounding OARs including cervix, uterus, bladder and rectum.
Anus and rectum	2D/3D T2 (FSE)	T2 sequences are suitable for distinguishing GTV and OARs including sigmoid colon and bladder.
Pancreas and liver	2D/3D T2 FSE 3D T1 + contrast + fs	Breath-hold or navigator triggered. Option of using abdominal compression to minimise respiratory motion. If difficult for patients to hold breath, can acquire image with multiple signal averages to average out motion. Acquisition of T1 + contrast + fs images in the arterial, venous and delayed phases allows vessels to be depicted which can assist with delineation.

Table 9. MRI for RT sequences for a range of tumour sites which can act as a primer for centres that are starting to include MRI in the RT workflow. Abbreviations: gradient echo (GE), fast spin echo (FSE), fat saturation (fs), fluid attenuated inversion recovery (FLAIR).

Section 8 Quality assurance

Key messages of section:

- *Standard QA requirements aimed at diagnostic radiology services are also essential for MRI for RT planning.*
- *Additional QA requirements in MRI for RT planning relate to communication with patients, couch motion, positioning lasers and geometric accuracy.*
- *Ideally a QA programme should be tailored to specific RT workflows, as requirements vary.*
- *We recommend investigating and documenting the maximum residual distortion-related displacement expected within the volume of interest for each RT clinical workflow.*

8.1 Introduction

The objective of a QA programme is to ensure that the MRI system meets the needs of the service and of the users throughout its working life. IPEM, ACR (American College of Radiology) and AAPM (American Association of Physicists in Medicine) provide detailed advice on measurements of signal parameters (SNR, uniformity, stability), image parameters (resolution, geometric fidelity, slice profile and position), image contrast characteristics and quantitative measurements (relaxation times, diffusion parameters and others) (McRobbie and Semple 2017, ACR 2017, Jackson *et al* 2010). These documents address generically the needs of a diagnostic radiology service and provide action values for QA measurements.

Regular testing of signal and image parameters form the basic framework for MRI QA and the standards proposed are also recommended for MRI in RT planning. They include frequent testing of SNR and uniformity in receiver coils, which is sensitive to the common failure of individual array elements. All MRI manufacturers provide their customers with test objects and software to perform basic receiver coil QA and we recommend their use in addition to more detailed tests of image quality. Acceptance testing of an MR scanner for RT also follows the same general principles as for a diagnostic MR system used within a radiology service. It includes image quality tests as well as ensuring that the hazards due to magnetic fields and cryogens are adequately controlled – see Section 4.3.

This section highlights aspects of MRI QA which are particularly relevant to RT planning users and it contains additional recommendations to the basic requirements described above, in agreement with current literature (Kapanen *et al* 2013, Liney *et al* 2013, Xing *et al* 2016, Paulson *et al* 2015, Glide-

Hurst *et al* 2015, Mah *et al* 2002). A minimum frequency is proposed for these additional tests. It is acknowledged that the need to document system performance may lead to more frequent testing.

The emergence of MR-linacs and MRI-only RT planning are beyond the scope of this guidance. However, each will have more stringent QA requirements than those discussed in this section and they warrant separate guidance. A first step towards this guidance for MR-linacs is work describing commissioning and results across multiple Elekta Unity systems (Tijssen et al 2019).

8.2 QA in MRI for RT

The following areas require additional testing in MRI for RT planning: patient communication, patient couch geometry, positioning lasers and geometric accuracy. A summary of the recommendations for QA tests to be performed, their frequency and the action levels is shown in Table 10. In this section acceptance testing is defined as ensuring that the MR scanner is set up and handed over from the manufacturer as expected and commissioning is defined as ensuring that the process for a specific RT workflow is accurate. Action values are defined as values that, if exceeded, would warrant further investigation to understand the origin of a breach. This will lead to either remedial action to return the measured parameter to within the expected range or mitigation to change clinical practice to ensure safe treatments.

Some of the tests in Table 10 are discussed below in more detail. Test methods are given as well as background information about the test.

Test	Section reference	Action values	Each examination	Daily	Monthly	Quarterly	Annually	After major upgrade	At commissioning	At acceptance testing
Patient communication systems test	Section 8.3	Communication failure	x							x
DICOM check	Section 8.4	Any incorrect parameter	x					x	x	
Assess for foreign objects in bore	-	Any foreign objects present		x						x

Manufacturer recommended daily QA	See manufacturer's guidance	Basic image quality test performed for consistency		x				x		x
Basic external laser alignment	Section 8.5 and (Patel 2018) Sections 3.5.2.4, 3.5.2.5 and 3.5.2.6	± 2 mm		x				x		x
Full external lasers check	Section 8.5 and (Patel 2018) 3.5.2.7, 3.5.2.8, 3.5.2.9 and 3.5.2.10	± 2 mm			x			x		x
Receiver coil check - SNR and uniformity	(McRobbie and Semple 2017, ACR 2017, Jackson *et al* 2010)	See references				+	x	x		x
Image quality tests	(McRobbie and Semple 2017, ACR 2017, Jackson *et al* 2010)	See references					x	x		x
Gradient-related geometric distortion	Section 8.6.1	Acceptance test: Document volume where displacement is > 1 mm and 2 mm. Ongoing action value: 2 mm within a clinically relevant volume			‡		x	x		x
Couch flatness and deflection under load	Section 8.7 and (Patel 2018) Section 3.5.2.12	0.2° laterally and 0.5° longitudinally, ± 2 mm deflection					x	x		x
Field inhomogeneity-related geometric distortion	Section 8.6.2	1-2 mm for most RT applications						x	x	
End to end QA	Section 8.8	2 mm for most RT applications						x	x	
SNR/image quality/B_0 field inhomogeneity-related distortion when employing RT accessories	Section 8.6.2 and 8.9	Clinical decision on SNR and image quality						x	x	

Table 10. Recommended QA procedures and minimum testing frequency.
+ – tests must be performed on all receiver coils quarterly for coils extensively used for RT purposes.
‡ – it is appropriate to measure gradient-related geometric distortion more frequently than annually until the stability of the MR scanner and the measurement procedure used has been demonstrated locally.

8.3 Patient communication systems

Method: Check patient communication systems (alarm bell, bore speakers) prior to the start of every MRI examination.

Background: The positioning of MRI patients in examinations performed for RT planning often limits their movement and ability to communicate with the operator (Section 4.4.2).

8.4 Inspection of DICOM files

Method: It is recommended to inspect all MRI data sets used in RT planning. Table 11 lists the main DICOM fields of interest that should be compared to the commissioned MRI sequence for a given RT planning application. This process can be automated with a script and will ensure consistency in acquisition parameters. Assessing these parameters is essential every time a data set of unknown characteristics is loaded into the RT planning system.

Tag	Name	Information
(0008, 103E)	Series Description	Indicates whether the correct sequence has been employed. Users can adopt a local convention to name sequences suitable for RT planning.
(0020, 0037)	Image Orientation (Patient)	Image orientation is a part of the protocol and it may not be possible to import images of some orientations into the TPS.
(0008,0008)	Image Type	Indicates whether post processing for gradient distortion correction has been applied.
(0018, 0095)	Pixel Bandwidth	(Hz/pixel) Taken in conjunction with pixel size, will provide information on expected displacements.
(0028, 0030)	Pixel Spacing	(mm) Information on spatial resolution.
(0018, 0050)	Slice Thickness	(mm) Information on spatial resolution.
(0018, 0088)	Spacing Between Slices	(mm) Information on gaps between slices.
(0018, 1312)	In-plane Phase Encoding Direction	ROW/COL. This field will allow identification of the readout direction.

Table 11. Fields of interest for RT planning in a DICOM data set.

Background: Inspection of DICOM files can contribute to the detection of a number of errors, for example: incorrect pulse sequence applied, distortion correction not applied (McWilliam *et al* 2018), unexpected image orientation, insufficient resolution, readout bandwidth too low, different orientation of phase encoding and readout gradient.

8.5 External lasers

Method: Every day that the RT lasers are used, perform a basic check of laser alignment as described by IPEM Report 81 for CT simulators (Patel 2018). Monthly, if RT lasers are used, perform the full laser check as described in IPEM Report 81.

Background: If lasers are used then the QA of these lasers should be consistent with the tests recommended for CT simulation in IPEM Report 81 (Patel 2018). The main additional consideration for laser tests for MR scanners is MR safety: the use of non-magnetic rulers and spirit levels is required.

8.6 Assessment of geometric distortion

Geometric distortion depends on both the linearity of the field produced by the gradient coils and the uniformity of the static magnetic field. These are considered separately in the following sections.

8.6.1 Gradient-related geometric distortion

Method: A large test object of known geometric properties must be used to characterise the geometric distortion associated with non-linear gradient fields over the useful field of view of the scanner (McWilliam *et al* 2018). The phantoms geometric properties can be taken from its design and construction or from CT images, presumed to be distortion free and it may be necessary to use CT to check the integrity of the test object throughout its lifespan.

Most commercial test object providers recommend a specific pulse sequence. For other cases a pulse sequence must be chosen to provide sufficient image quality to allow assessment of the distortion pattern. A basic 3D spin echo pulse sequence is recommended and images should ideally be free of artefacts. The sequence should have receiver bandwidth high enough to ensure that the geometric distortion is dominated by the characteristics of the magnetic field gradients and that the effects of the non-uniformity of the main magnetic field (and shimming) become negligible. The receiver bandwidth should be chosen to keep the water-fat chemical shift displacement under 0.5 mm; higher receiver bandwidths make the measurements noisier but more robust.

In order to verify that the magnetic susceptibility distribution within the test object has not contributed to the distortion pattern, it is recommended that two separate datasets acquired with different readout and phase encoding directions (in plane readout and phase encoding swap) are compared. Differences between the images can be attributed to the test object's own susceptibility distribution and such limitations must be either addressed or taken into account. Other methods are

the comparison of two separate datasets acquired either with different receiver bandwidths (Schmidt *et al* 2017) or with an inversion of the readout gradient direction (Chang and Fitzpatrick 1992).

Geometric accuracy must be assessed in acceptance testing and compared to the manufacturer's specification or previous results for similar MRI scanners, if available. It is recommended to place the test object in a reproducible position in relation to the magnet isocentre and, if it is possible to do so, MR images should be acquired both with and without the automated correction for gradient-related distortion provided by the manufacturer, keeping them for future reference. The residual distortion must be assessed quantitatively either using the test object's proprietary software, developing your own software or by performing a deformable MRI-CT image registration with the resulting deformation vector field being the assumed geometric distortion. The volume for which the displacements are greater than 1 and 2 mm must be documented, as these are limits beyond which systematic errors may be introduced in the RT workflow (Liney and van der Heide 2019). It is recommended that for standard RT applications an action level of 2 mm is used within the volume of clinical significance. This volume will depend on the specific workload within a given institution: it could be within a sphere of diameter 20 cm for a workload consisting of brains or prostates where only the central portion of scans are used for contouring or a sphere of diameter 40 cm for a workload consisting of full FOV head and neck or pelvis scans. For specialized RT applications such as intra-cranial SRS the action level should be lower and displacements of no more than 1 mm over the clinically relevant volume are advised. It is then recommended that residual geometric distortion is assessed at least annually, as it has been demonstrated that gradient-related geometric distortion is stable (Ahmed *et al* 2010, Mizowaki *et al* 2000, Petersch *et al* 2004, Mah *et al* 2002, Ranta *et al* 2019). It is recommended that geometric distortion tests are performed more frequently when introducing MRI into the RT workflow and then reduced in frequency to annually once institutions are confident that the results are stable from their MR scanner and the measurement procedure used locally. Assessing geometric distortion monthly also allows centres to maintain QA documents with the same frequency as for CT simulators used for RT-based planning.

Background: The QA for geometric accuracy used in diagnostic MRI does not meet the requirements of RT users, as the recommended measurements are often made over small volumes, employing small test objects and sometimes employing only 2D images in central planes. Post processing with the MRI manufacturer's own distortion correction software is often overlooked. Here measurements with a large test object are recommended to characterise the gradient hardware over the entire volume used in RT planning. The ideal test object should cause as little disturbance to the static magnetic field as possible and certainly no more disturbance than a typical human subject would provide.

Current MRI systems provide displacements less than 2 mm up to a distance of 250 mm from the isocentre (Ranta *et al* 2019) after the manufacturer's distortion correction has been applied, but displacements can still reach more than 5 mm further away from the magnet isocentre (Ahmed *et al* 2010, Mizowaki *et al* 2000, Petersch *et al* 2004, Mah *et al* 2002). It is recognised that the geometric distortion pattern is stable (Ahmed *et al* 2010, Mizowaki *et al* 2000, Petersch *et al* 2004, Mah *et al* 2002, Ranta *et al* 2019), as it simply depends on gradient-coil design and manufacture. The function of routine geometric distortion testing is simply to detect the unlikely event of major damage to the gradient coils, compromising their integrity, or changes to the distortion correction software.

From a practical point of view, the residual image distortion only needs to be assessed after post-processing with the manufacturer's own distortion correction software, as it is this residual image distortion that has a direct impact in RT planning applications. However, it is important to store images with and without distortion correction for reference: MR systems will have many software upgrades in their working life and it is therefore desirable to distinguish software and hardware changes.

8.6.2 B_0 field inhomogeneity-related distortion

Method: It is recommended that the following information is documented during commissioning of each MRI workflow used in RT planning: the volume of interest, the maximum acceptable geometric error and the maximum expected field inhomogeneity within the volume of interest. The maximum expected field inhomogeneity should either be estimated (see Section 7.3) or measured during commissioning (using an MRI manufacturer's provided B_0 field mapping sequence), with the displacement along the readout direction calculated. The interpretation of any measurement results requires MRI expertise – the involvement of clinical scientists specialised in MRI is recommended. The volume of interest must include expected outlines of target volumes and OARs used in RT planning, in addition to any other structures and landmarks used in MRI-CT registration. It is generally agreed that a residual distortion error of 2 mm is acceptable for most general RT applications (Liney and van der Heide 2019). However, for some specific workflows (such as intracranial SRS) a more stringent tolerance of 1 mm is more appropriate; the appropriate limit should be decided on locally. The distortion error tolerance discussed here is the acceptable distortion within the RT volume of interest (and not the whole imaging field). It is expected that the MRI sequences will be optimised to keep the calculated expected distortion error smaller than the maximum acceptable distortion error displacement (see Section 7.3). Acquiring B_0 field maps for each individual patient study is only recommended in a very small number of critical applications, where minor distortions cannot be tolerated (e.g. MR-guided RT, SRS in the presence of metallic implants). For most applications it is sufficient to determine whether the field inhomogeneity is comparable to the fat-water chemical shift

(3.5 ppm). If sequences are optimised based on the fat water shift of 3.5 ppm as recommended (see Section 7.3), any expected field inhomogeneity not exceeding 3.5 ppm will lead to geometric distortion errors that are clinically acceptable.

When commissioning RT accessories, the volume where geometric errors exceed the locally determined tolerances must be documented and communicated to users. As described in Section 8.6.1, displacements can be measured by comparing images acquired with different readout and phase encoding directions (in plane readout and phase encoding swap) or with inversion of the readout gradient direction (Chang and Fitzpatrick 1992). If patient-specific field mapping is being used, the measurement should be made with RT accessories in place, after the final shimming over the volume of interest, which must be maintained during the examinations (Section 7.3).

Background: covered in section 7.3.

8.7 Patient couch flatness

Method: The couch flatness must be tested with an MR Safe or MR Conditional spirit level, by bringing different portions of the couch to the laser isocentre and to the magnet isocentre. The testing should cover the full range of couch motion and be undertaken with the couch loaded and unloaded. The couch should be weighted with test objects comparable to the weight of a patient. Images should also be checked digitally by checking horizontal structures in a suitable test object. The action limit on flatness is 0.2° laterally and 0.5° longitudinally and is the same as that recommended for CT simulators (Patel 2018). This testing should be performed at acceptance testing and then annually.

Background: The same QA framework applies to couch testing for MRI as for CT, as discussed in IPEM Report 81 (Patel 2018). MRI flat top couches are generally an overlay and there is the potential that these are not flat. They are supported on the sides and not cantilevered, like CT couches, so may behave differently.

8.8 End to end QA

Method: In end to end QA, a single test object, with structural details visible in MRI and CT and ideally anthropomorphic, is scanned with a given clinical protocol in MRI and CT, and the patient workflow is reproduced exactly: MRI and CT images are transferred to the TPS and registered. The registration is then assessed, either visually or quantitatively, using the methods discussed in Section 9. The setting

of an action level depends on the specific workflow: 2 mm is recommended for most RT applications; however, more stringent values are required for critical applications such as intracranial SRS.

Background: End to end testing has the advantage that all aspects of the patient workflow are evaluated: MRI and CT resolution, contrast and geometric fidelity, data transfer, data integrity and performance of the registration software. This type of QA is therefore ideal to ensure parity between different equipment and longitudinal stability for a given RT planning service. However, there are some limitations, the main one being that the test is not very specific to the point of failure and hence a failure requires further investigation. A further problem is that the test object may not adequately represent the clinical situation. For example, the phantom may be easier to shim than a human subject and a good result with the test object may not be replicated in a patient study. There is still value in end to end QA though, as it tests the whole workflow and ensures data transfer is working correctly before scanning patients. End to end QA is commonly used when commissioning RT pathways, for example stereotactic radiosurgery procedures (e.g. using the stereotactic end-to-end verification (STEEV) phantom (Dimitriadis *et al* 2017)).

8.9 QA of RT accessories

Method: Reduction in SNR, changes to image quality, spurious signals and localised effects on B_0 field homogeneity (see Section 8.6.2) must be characterised and documented when RT accessories are commissioned. SNR and uniformity can be measured at the centre of a large test object (or within a healthy volunteer, if permitted locally), with and without the accessories, using the same sequence and receiver coils. Images can be compared to assess the effect of the RT accessories. This will inform the decision on the range of use of the RT accessory and if any measures are needed to compensate for a loss of SNR, such as increasing the number of averages or decreasing the resolution. Methods to detect B_0 inhomogeneity associated with auxiliary equipment were discussed in Section 8.6.2.

Background: MRI for RT planning is likely to involve the use of specific accessories (see Sections 2.3, 6.2 and 6.4), many of which will cause a reduction in SNR by increasing the distance between the patient and the coil. Uniformity changes may also occur in association with modifications to receiver coil arrangements. Some MR scanners offer more than one type of uniformity correction and the best option can therefore be identified for each arrangement of receiver coils (Liney *et al* 2013). In addition, some accessories may provide MR signals due to the materials used in manufacture. It is recommended to perform SNR measurements when RT accessories are commissioned. It is also

possible that the introduction of a positioning device may have a detrimental effect on the geometric integrity of the images if the device introduces B_0 field inhomogeneity, as is possible even with MR Safe devices. Assessment of geometric distortion due to field inhomogeneity was discussed in Section 8.6.2 and also relates to RT accessories. Only in extreme cases would an electrically conductive accessory affect the B_1 field; in that case both image quality and standard MR safety considerations apply, as discussed in Section 4.

Section 9 MRI to CT image registration

Key messages of section:

- *Practical examples are given to aid rigid image registration in different anatomical regions.*
- *A commissioning and a per-patient verification process should be set up.*
- *A documented request for the registration must be made by the referring clinical oncologist. For ease the required information should be defined in a clinical protocol. Recommendations of what to include in such a protocol are given.*
- *Communication of the registration quality should be included in a report produced by the operator. Recommendations of what to include in the report are given.*

9.1 Introduction

Registrations can be either global, where registrations are optimised over the whole image – suitable if the patient position is very consistent – or local, where registrations are optimised within a restricted guiding region of interest (ROI). Furthermore, registrations can be manual, where there is full user interaction, automatic, where an algorithm optimises the registration, or a hybrid. An introduction to the different concepts involved in MRI-CT registration theory can be found in the literature (Maintz and Viergever 1998, Brock *et al* 2017, Liney and van der Heide 2019). This section includes some clinical examples of RIR and discussion on how to practically commission and quality assure the process in an RT clinic. The AAPM TG-132 report (Brock *et al* 2017) provides a thorough discussion of image registration in RT and it is recommended that centres follow the principles of that report and are compliant with its recommendations. This section aims to highlight and give practical advice on how centres can be compliant with the AAPM TG-132 recommendations. Deformable registration is not widely used in the clinic and was considered beyond the scope of this report but it has been covered in the literature (Brock *et al* 2017, Liney and van der Heide 2019).

9.2 Overview of registration procedure

In the clinic an automatic RIR is typically recommended. The pipeline for performing an MRI-CT registration is as follows:

1. Import both the MRI and CT image data sets into the image registration software.
2. Perform an initial manual RIR to act as a seed point to align the MRI to the CT optimally in the region where the MRI will be used for contouring.
3. If necessary, define an ROI that encapsulates the anatomy of interest. This ROI will define the region used to guide a local registration and should include all anatomy that will be delineated on the MR image. Example guiding ROIs are given for different anatomical sites in Section 9.3. If the internal and external anatomy is the same in both MRI and CT images, then an ROI is not required and a global registration can be used. However, if the anatomy is different between the two images (either externally, due to the patient not being immobilised the same, or internally, due to internal anatomy differences such as bladder filling) then the ROI has to be optimised to have enough information to be able to perform a registration, but not so much information that regions not of clinical interest are included.
4. Perform an automatic RIR, either globally or locally, guided by the ROI defined above. If the maximum number of iterations is reached before the similarity metric stops improving, it may be possible to improve the registration by repeating this step. It is important that this automatic RIR is manually checked by someone of adequate competence/experience and that manual optimisation may be required if the result is not suitable.

The greater the difference in patient positioning between the MRI and CT images, the greater the difficulty in performing the registration process and the less likely it is to get good agreement in all parts of the image. For example, for a brain, MRI anatomy outside the cranium (i.e. in the oral cavity or the mandible) may vary significantly between CT and MRI and hence should not be included.

Image registration software typically assumes that MR images acquired in the same session are in the same position. The consequence of this is that it is only necessary to register one 3D MR image to a 3D CT image provided all the MR images were in fact acquired on the same isocentre, and the transformation is propagated to all other MR images acquired in the same session. This is useful when using multiple MR images for delineation. However, care must be taken to ensure that the patient is in the same position for all the MR images. In cases where patients are not adequately immobilised in

the MRI session and there is patient movement, each MR image must be registered to the CT individually.

9.3 Clinical examples of RIR

9.3.1 Brain

It is not uncommon for patients with brain lesions to have surgery before RT. If this is the case, then it is vital that the MR and CT images are both acquired a suitable time post-surgery to allow swelling to reduce. If the swelling caused by surgery is on one image and not the other, then results of the registration will be degraded. It is important that the guiding ROI for the registration is limited to the cranium, i.e. does not include the mandible or the neck, due to potential movements in these regions which, if included in the local registration, can reduce registration quality. An example registration from the brain including a recommended guiding ROI is displayed in Figure 7.

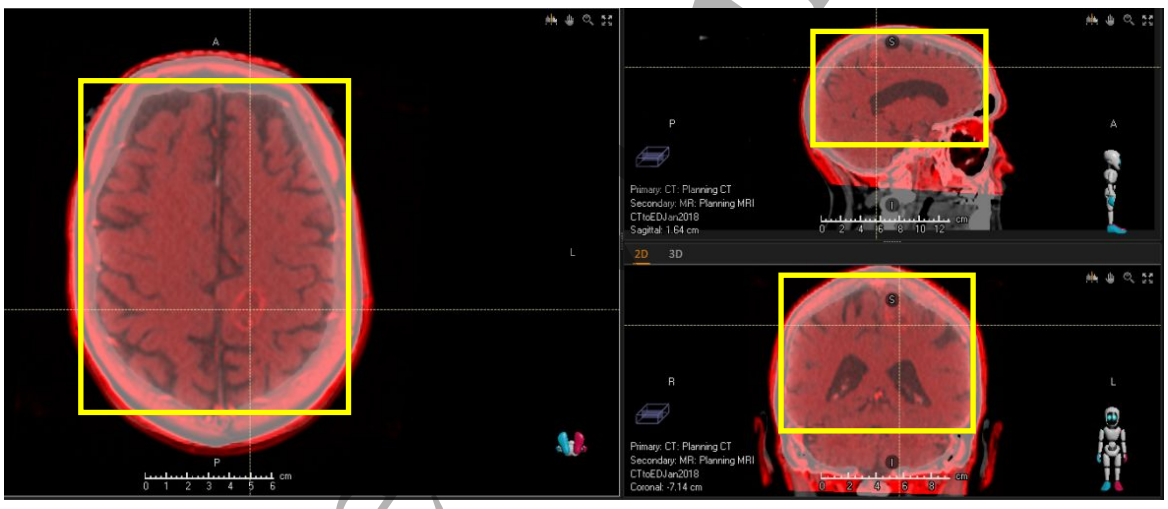


Figure 7. Local RIR for a patient with a glioblastoma. Grey overlay images are CT and red overlay images are MRI. The recommended guiding ROI used for local registration is shown in yellow.

9.3.2 Head and neck

If the MR and CT images are both acquired using the same immobilisation, then it is recommended that a global RIR is used. However, in some cases even though effort has been made to immobilise the patient's external anatomy, the internal anatomy can vary, e.g. tongue position. If there are regions where the internal anatomy differs between images, then image registration results may be improved by performing a local registration with a guiding ROI that excludes this anatomy. An example global RIR is shown in Figure 8.

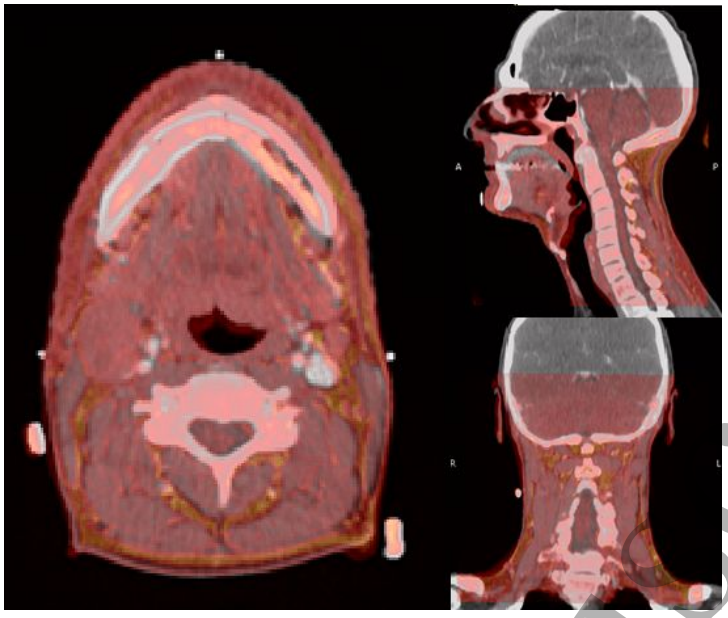


Figure 8. Global RIR for a patient with an oropharyngeal squamous cell carcinoma. Grey overlay images are CT and red overlay images are MRI.

9.3.3 Abdomen/thorax

In the abdomen, breathing motion can result in motion artefacts or images being acquired in different phases of the breathing cycle. When images are acquired in breath-hold with the same immobilisation then global RIR is recommended. However, even when care is taken to reproduce patient set up and imaging in the same breathing phase, it is not uncommon to observe tissue differences between MRI and CT, due to the deformable nature of soft tissue in the abdomen. In this case it is recommended that a guiding ROI is used for local RIR that includes just the organ of interest. If deformation is still present with reduced registration accuracy, then a smaller guiding ROI should be used including only the anatomy of interest. An example RIR in the liver is shown in Figure 9. It is recommended that any deviation from the protocol recommendation of a global RIR is documented and any regions that have compromised image registration quality are clearly documented so that the user of the registration understands this.

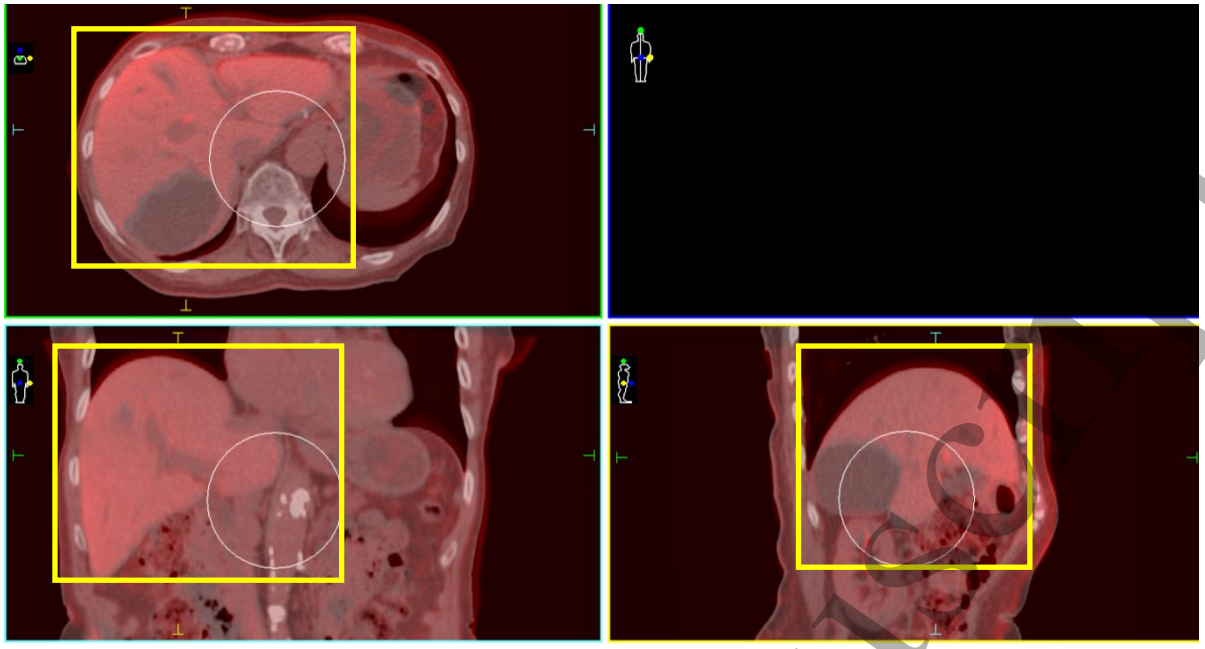


Figure 9. Local RIR for a patient with a liver metastasis. Grey overlay images are CT and red overlay images are MRI. The recommended guiding ROI for the local registration covers the whole liver and is shown in yellow.

9.3.4 Pelvis

For pelvic imaging, even when care is taken to reproduce patient set-up on MRI and CT, it is not uncommon to have soft tissue differences (e.g. around the bladder, bowel or rectum). Therefore, it is recommended that a local RIR is performed with a guiding ROI optimised for the anatomy of interest, unless the anatomy of interest is very close to bone (and hence a bone-based registration is a good surrogate for the tissue of interest). It is recommended that registration is performed in two stages, the first using a guiding ROI including bony anatomy and the second using a smaller guiding ROI including just the soft tissue of interest. For example, in the prostate, when implanted fiducial markers are not used, a first registration should be guided by bony anatomy and the final registration should use a guiding ROI including just the soft tissue around the prostate capsule. An example of guiding ROIs from both stages is shown in Figure 10.

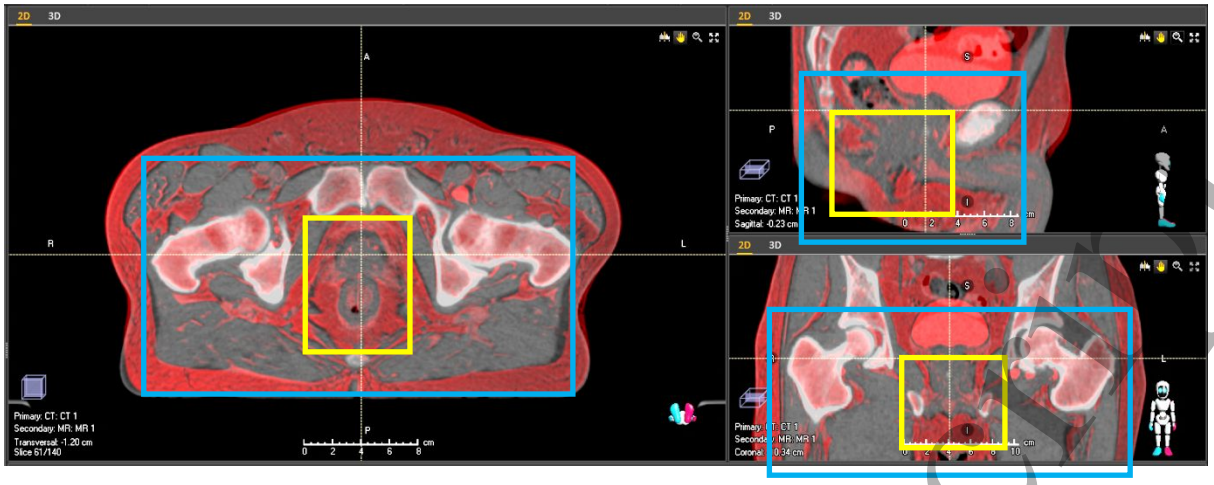


Figure 10. Local RIR for a patient with a prostate carcinoma. Grey overlay images are CT and red overlay images are MRI. The recommended guiding ROIs used for the initial bony based and final soft tissue local registrations are shown in blue and yellow respectively.

9.4 Recommended commissioning and per-patient verification QA for MRI-CT registration

There are two components to ensure a good QA programme for image registration: commissioning and individual patient verification.

- Commissioning (referred to in AAPM TG-132 as validation) is the process of evaluating the entire workflow in order to ensure that accurate registration can be achieved consistently. The commissioning processes should result in a characterisation of how the image registration software, algorithms and data transfer handle patient data. In addition, phantoms can be used to assess registrations against a known ground-truth, although phantoms are not typically representative of patients, so they are only of limited use. This process should be performed where setting up a new image registration software/TPS and when there is a significant change to the current pathway (i.e. software upgrades or new MRI scanner).
- Verification is the act of ensuring that the accuracy of a specific registration for a given patient is acceptable for the intended use.

The recommended tests for both commissioning and verification are summarised in Table 12, as well as in the literature (Brock *et al* 2017, Liney and van der Heide 2019). At the commissioning stage, quantitative tests are required to verify that data is transferred correctly and that registration is performed as expected. However, on a per-patient basis, qualitative tests are more common, as there is no known or expected result to compare the registration to. Where action levels are given they are taken, in part, from Brock *et al* 2017.

Test	Section reference	Action levels, where appropriate
Commissioning and after upgrade to software or MRI/CT scanners		
End to end test with physical phantom	Section 8.9	-
Physical phantom tests	Section 9.4.1	Data transfer is exact and geometric tests > minimum voxel dimension on both CT and MRI
Digital phantom registration accuracy	Section 9.4.2	Half of the largest voxel dimension
Clinical data registration accuracy	Section 9.4.3	-
Qualitative assessment	Section 9.4.3.1	No gross errors
Target registration error (TRE)	Section 9.4.3.2	Mean TRE > minimum voxel dimension
Contour comparison assessment	Section 9.4.3.3	MDA > 2–3 mm and/or DSC < 0.9
Consistency and transitivity	Section 9.4.3.4	Both < maximum voxel dimension
Per-patient verification		
Qualitative assessment	Section 9.4.4	No gross errors

Table 12. Recommended commissioning and per patient verification tests for MRI to CT image registration, modified from (Brock *et al* 2017, Liney and van der Heide 2019)*. MDA – mean distance to agreement, DSC – Dice similarity coefficient both of these parameters are described in the previous 2 references.*

9.4.1 Physical phantom test

Images of the physical test object used for end to end testing (Section 8.9) should be acquired in every available orientation, for example head-first supine, feet-first supine, etc., on both CT and MRI and DICOM tags checked to ensure all orientations are labelled correctly. MRI and CT images should be transferred to the registration software or TPS and accurate transfer of patient orientation, image acquisition parameters and demographics should be verified. Furthermore, image geometry should be assessed independently on the MRI and CT by measuring distances between details in the phantom and comparing to the known values, with a tolerance of the maximum voxel dimension for the difference between measured and known values. These tests should be repeated with MR images acquired with the phantom rotated at an angle of up to 45 degrees to ensure that the registration software or TPS is correctly processing tilted datasets.

How a TPS treats registration of multiple MRIs acquired during the same session should be determined using a physical phantom. For example, some software will link all images acquired during the same session and apply a transformation calculated from one image set to all the images. This can cause

issues if significant changes to patient anatomy (e.g. bladder filling) or positioning (e.g. coughing/gross patient movement) occurred during the MR imaging session. In these circumstances a new transformation may be necessary for different image sets and a documented process to allow this is required (using either software functionality or another workaround). This process should be tested by acquiring an MRI of the phantom and then translating and/or rotating it on the couch (without moving the couch) and acquiring a second image of a different image weighting. In order to register both these images to the same CT images, a different transformation is required for each. The process developed should be able to achieve this.

9.4.2 Digital phantom registration accuracy

Digital phantoms are patient or phantom images that have degraded image quality or known transformations applied (shifts, rotations or deformations). Testing patient digital phantom data is important during commissioning as it allows assessment of the registration with representative data where a ground truth is known. Digital phantoms can be made in house from local patient data or are available from the authors of AAPM TG-132. It is important that digital phantoms are representative of clinical shifts and rotations for the test to be useful. Digital phantoms with known differences should be imported into the registration software and a registration performed. The registration software should be able to undo the known shifts and rotations accurately. This can be assessed by ensuring the shifts and rotations reported from the registration are equal and opposite to the known applied values. If the registration software doesn't report these values, then the positions of landmarks visible on the registered datasets can be checked, to ensure that they coincide. The suggested action level is half of the largest voxel dimension.

9.4.3 Clinical data registration accuracy

It is important for commissioning that a representative clinical data set is used for testing, including at least ten patients. These should be acquired with the same acquisition parameters on the same scanners with the patient immobilised in the same way. Using these data sets, the proposed clinical registration pathway should be followed and the results assessed using the qualitative and quantitative methods discussed below. If this commissioning is not possible, for instance because the required data set is not available, then it is recommended that the following tests are performed prospectively as clinical data is being acquired.

9.4.3.1 Qualitative assessments

Qualitative assessments of image registration are commonly undertaken by visualising the resulting fusion. This relies on the clinical knowledge of whoever is assessing the registration to ensure that the fusion is acceptable. Gross errors can be easily detected by visual inspection, but care must be taken to detect more subtle errors. The common methods for assessing fusion qualitatively are split screen and checkerboard, image overlay, contour mapping and difference image. If qualitative assessment is performed with the multidisciplinary team that will be involved in using the clinical results, then it is a good opportunity for staff to learn about the strengths and limitations of the registration technique.

9.4.3.2 Target registration error

The target registration error (TRE, also referred to as Euclidean distance) is the residual distance between a set of corresponding landmarks that are identified on each image set after registration. A perfect alignment of the images results in a TRE of 0 mm. One difficulty of this technique is identification of suitable points on each dataset, especially in the case of MRI to CT registration, where image contrast differs between the modalities. In addition, there is some uncertainty in the identification of landmark locations on each image dataset and therefore there will always be a residual TRE, so averaging over multiple points is recommended with points selected close to the anatomy of interest. One problem with using TRE is that the results can be biased, due to landmarks being selected that are easily visible on MRI and CT. These regions are also likely to be better registered by an automatic registration algorithm. During the commissioning process it is recommended that TRE is assessed as a mean over multiple points, with a suggested action level of the minimum voxel dimension.

9.4.3.3 Contour comparison assessment

Image registration quality can be assessed by contouring structures on both CT and the registered MRI. If the registration is perfect, then the contours should be the same. This assumes that the structures appear the same on both modalities and there is no user error in defining the contours. There is an inherent bias in contour comparison methods because structures selected will be ones where the boundaries are clearly visible on MRI and CT. There may be a poorer registration result in regions where structures are not so clearly seen on CT. Furthermore, contour comparison metrics do

not provide evidence that a registration is correct, as they do not have a concept of corresponding points on each contour. As an example of where these metrics could produce misleading results, two spherical contours with the same size and centre of mass will match perfectly, regardless of any rotation of the volume about the central point. There are many metrics for comparing contours, with two common examples being mean distance to agreement (MDA) and Dice similarity coefficient (DSC). The suggested action levels for MDA and DSC are more than 2 mm and less than 0.9, respectively.

9.4.3.4 Consistency and transitivity

Consistency measures whether a registration is robust by registering the image in both directions. For example, firstly registering MRI A to the CT and then registering the transformed MRI A' back to itself. The resulting two transformations should be the inverse of each other with the same magnitude but opposite directions. Points of interest defined in image A should return to their original position after applying both transformations. Consistency should be assessed for a variety of representative patients during commissioning to ensure all points have a consistency measure of under the maximum voxel dimension.

If more than two images are available, for example if a CT and two MRI sequences have been acquired (MRI A and MRI B), then the transitivity can be determined, which is a measure of registration accuracy around a loop (as proposed by van Herk et al 1998). A combination of the transformations from MRI A to MRI B and MRI B to the CT should equal the transformation from MRI A to CT. Performing these registrations for a sample of representative patients during commissioning is recommended to ensure all points have a transitivity measure of under the maximum voxel dimension.

Measuring the consistency and transitivity of a registration cannot determine which transformation is incorrect, so it is not a very specific test. There is also the possibility that equal and opposite errors can be missed. Furthermore, some image registration algorithms can be set to ensure consistency during the optimisation procedure, negating the usefulness of this test.

9.4.4 Per-patient verification

On a per-patient basis, a registration should be assessed to determine whether it is acceptable for the required use (as defined in the protocol by the clinical oncologist who will use the result of the registration). As there is no known ground truth, it is not possible to quantitatively measure the accuracy of the registration. Therefore, qualitative assessment of the registration quality should be

undertaken by two independent people using the methods described in Section 9.4.3.1. It is important that the two independent people have sufficient training and experience to understand the consequences of errors in the registration. Usually the first person is the operator (for example, a dosimetrist) undertaking the image registration process and the second is the end user of the fusion (for example, a clinical oncologist who will formally accept the registration result). It is important for the operator to report the accuracy of the registration in an unambiguous manner. It is recommended that the uncertainty in the registration is reported using a standardised methodology defined within AAPM TG-132 with an uncertainty assessment of 0 to 4 (Brock *et al* 2017). This should be done in such a way (ideally electronically) that it remains part of the patient record of the treatment, aiding clear communication between the different parties involved in the patient's treatment pathway.

9.5 Request and report documentation for image registration

Clear documentation that communicates what is expected from the registration and the quality of the final registration is important to ensure that all staff involved in the patient's care are clearly informed. The AAPM TG-132 group formalises this documentation in two stages (Brock *et al* 2017): a request for registration from the clinical oncologist and a report on the quality of the result from the operator. Both the request and report should be made in such a format that it is part of the patient's treatment record and is available for all members of the patient's treatment care team. Rather than an individual detailed request for a registration for each patient, we recommend for simplicity and consistency that the MRI-CT registration procedure used for each anatomical group should be documented in a clinical protocol. When a clinical oncologist requests a registration for a patient, they can specify a given protocol while highlighting any deviations they require from that clinical protocol.

It is likely that, for each anatomical site, the following information will be the same for all patients and therefore should be included in the protocol:

- Image datasets to be registered, specifically identifying which MRI sequence is required (including sequence names, if these have been standardised).
- The structures which will be contoured on the MRI, in order to identify anatomy of interest for focusing the image registration.
- The registration method, including the software and any specific options available.
- The accuracy required, including details of any key areas that may be used for a local registration, if that is acceptable.

Once the operator has performed the registration according to the clinical oncologist's request, they should fill in a report on the result which should include at least the following:

- Any deviation necessary from the clinical protocol to perform the registration.
- Comments on the accuracy of results, using the nomenclature described by AAPM TG-132. Regions where registration is too poor to be used clinically must be clearly highlighted (using annotated images if appropriate).

Acknowledgments

The authors would like to thank IPEM for supporting the working group and IPEM, SCoR and the Faculty of Clinical Oncology of RCR for endorsing these guidelines. Furthermore the following are thanked Mr Chris Forrest for guidance and feedback on the experiences at the Leeds Cancer Centre and discussion about what to consider on MRI procurement site visits, Dr Louise Murray for discussion about what to consider on MRI procurement site visits, Mrs Helen Shepherd for providing general comments and feedback on the draft text and Mrs Sarah Wright for useful discussion and guidance regarding MRI couch QA.

Dr Richard Speight is supported by the Sir John Fisher Foundation and Cancer Research UK Centres Network Accelerator Award Grant (A21993) to the ART-NET consortium. Dr Ben George is partly supported by a Cancer Research UK Centres Network Accelerator Award Grant (A21993) to the ART-NET consortium. Dr Cynthia Eccles is supported by the NIHR Manchester Biomedical Research Centre. Mr Michael Dubec is supported by Cancer Research UK via the funding to the Cancer Research UK Manchester Centre: [C147/A18083] and [C147/A25254].

The author's have confirmed that any identifiable participants in this study have given their consent for publication.

References

ACR 2017 *American College of Radiology MR Accreditation Program. Testing Instructions*

Adjeiwaah M, Bylund M, Lundman J A, Söderström K, Zackrisson B, Jonsson J H, Garpebring A and Nyholm T 2019 Dosimetric Impact of MRI Distortions: A Study on Head and Neck Cancers *Int. J.*

Radiat. Oncol. Biol. Phys. **103** 994–1003

Ahmed M, Schmidt M, Sohaib A, Kong C, Burke K, Richardson C, Usher M, Brennan S, Riddell A, Davies M, Newbold K, Harrington K J and Nutting C M 2010 The value of magnetic resonance imaging in target volume delineation of base of tongue tumours - A study using flexible surface coils *Radiother. Oncol.* **94** 161–7 Online: http://dx.doi.org/10.1016/j.radonc.2009.12.021

Brock K K, Mutic S, McNutt T R, Li H and Kessler M L 2017 Use of image registration and fusion algorithms and techniques in radiotherapy: Report of the AAPM Radiation Therapy Committee Task Group No. 132 *Med. Phys.* **44** e43–76 Online: https://aapm.onlinelibrary.wiley.com/doi/abs/10.1002/mp.12256

Bronskill M J, Carson P L, Einstein S, Koshinen M, Lassen M, Mun S K, Pavlicek W, Price R R and Wright A 1986 *Site Planning for Magnetic Resonance Imaging Systems*

BS 2010 *BS EN 60601-2-33:2010* Online: https://shop.bsigroup.com/ProductDetail/?pid=000000000030352895

Cancer Research UK 2015 Achieving World Class cancer outcomes: Stratergy 2015 - 2020

Chandarana H, Wang H, Tijssen R H N and Das I J 2018 Emerging role of MRI in radiation therapy *J. Magn. Reson. Imaging* **48** 1468–78

Chang H and Fitzpatrick J M 1992 A technique for accurate magnetic resonance imaging in the presence of field inhomogeneities *IEEE Trans. Med. Imaging* **11** 319–29

Christian Gustafsson, Maja Sohlin and Lars Filipsson 2016 *Method book for the use of MRI in radiotherapy* Online: http://gentleradiotherapy.se/wp-content/uploads/2016/12/Metodbok_version3_2016-12-15_ENG_final.pdf

Dimitriadis A, Palmer A L, Thomas R A S, Nisbet A and Clark C H 2017 Adaptation and validation of a commercial head phantom for cranial radiosurgery dosimetry end-to-end audit *Br. J. Radiol.* **90** 1–9

Doran S J, Charles-Edwards L, Reinsberg S A and Leach M O 2005 A complete distortion correction for MR images: I. Gradient warp correction. *Phys. Med. Biol.* **50** 1343–61

Eccles C L, McNair H A, Armstrong S E A, Helyer S J and Scurr E D 2017 In response to Westbrook – Opening the debate on MRI practitioner education *Radiography* **23** S75–6

Edwards T 2019 Building MR-simulation competency in radiotherapy *Philips FieldStrength Artic.* Online: https://www.philips.co.uk/healthcare/education-resources/publications/fieldstrength/developing-a-model-of-best-practice-in-a-new-mr-sim-service

Glide-Hurst C K, Wen N, Hearshen D, Kim J, Pantelic M, Zhao B, Mancell T, Levin K, Movsas B, Chetty I J and Siddiqui M S 2015 Initial clinical experience with a radiation oncology dedicated open 1.0T MR-simulation *J. Appl. Clin. Med. Phys.* **16** 218–40

Hargreaves B, Worters P W, Pauly K B, Pauly J M, Koch K M and Gold G E 2011 Metal Induced Artifacts in MRI *AJR Am J Roentgenol* **197** 547–55

Hua C ho, Uh J, Krasin M J, Lucas J T, Tinkle C L, Acharya S, Smith H L, Kadbi M and Merchant T E 2018 Clinical Implementation of Magnetic Resonance Imaging Systems for Simulation and Planning of Pediatric Radiation Therapy *J. Med. Imaging Radiat. Sci.* **49** 153–63 Online: https://doi.org/10.1016/j.jmir.2018.02.054

Hua C and Uh J 2019 *Philips Radiation oncology - How do you commission and implement an MRI system for radiation therapy planning?* Online: https://philipsproductcontent.blob.core.windows.net/assets/20191119/a6fa1f759b434b83b68cab0a00f1905c.pdf

IEC 2016 *IEC 60601-2-33:2010/COR2:2016* Online: https://webstore.iec.ch/publication/24208

IEC 2010 *IEC 60601-2-33:2010* Online: https://webstore.iec.ch/publication/2647

IPEM 2013 *POLICY STATEMENT: Scientific Safety Advice to Magnetic Resonance Imaging Units that Undertake Human Imaging* Online: https://www.ipem.ac.uk/Portals/0/Documents/Publications/Policy Statements/IPEM_MRSafetyExpert_PolicyStatement_04102013_SK.pdf

IPEM MR-SIG Working Party 2017 *IPEM MR-SIG Working Party Report: Recommendations for MRI Safety Notices* Online: https://www.ipem.ac.uk/ScientificJournalsPublications/MRISafetyNotices.aspx

Jackson E, Bronskill M, Drost D, Och J, Pooley R, Sobol W and Clarke G 2010 *AAPM report 100 - Acceptance Testing and Quality Assurance Procedures for Magnetic Resonance Imaging Facilities*

Jafar M M, Reeves J, Ruthven M A, Dean C J, MacDougall N D, Tucker A T and Miquel M E 2016 Assessment of a carbon fibre MRI flatbed insert for radiotherapy treatment planning *Br. J. Radiol.* **89** 1–7

Johnstone R I, Guerrero-Urbano T, Michaelidou A, Greener T, Miles E, Eaton D and Thomas C 2020 Guidance on the use of MRI for treatment planning in radiotherapy clinical trials *Br. J. Radiol.* **93** 20190161

Kapanen M, Collan J, Beule A, Seppälä T, Saarilahti K and Tenhunen M 2013 Commissioning of MRI-only based treatment planning procedure for external beam radiotherapy of prostate *Magn. Reson. Med.* **70** 127–35

Koch K M, Brau A C, Chen W, Gold G E, Hargreaves B A, Koff M, McKinnon G C, Potter H G and King K F 2011 Imaging near metal with a MAVRIC-SEMAC hybrid *Magn. Reson. Med.* **65** 71–82

Koch K M, Lorbiecki J E, Hinks R S and King K F 2009 A multispectral three-dimensional acquisition technique for imaging near metal implants *Magn. Reson. Med.* **61** 381–90

Latifi K, Caudell J, Zhang G, Hunt D, Moros E G and Feygelman V 2018 Practical quantification of image registration accuracy following the AAPM TG-132 report framework *J. Appl. Clin. Med. Phys.* **19** 125–33

Liney G P and van der Heide U A 2019 *MRI for Radiotherapy Planning, Delivery, and Response Assessment* (Springer Press)

Liney G P, Owen S C, Beaumont A K E, Lazar V R, Manton D J and Beavis A W 2013 Commissioning of a new wide-bore MRI scanner for radiotherapy planning of head and neck cancer *Br. J. Radiol.* **86**

Liney G P, Whelan B, Oborn B, Barton M and Keall P 2018 MRI-Linear Accelerator Radiotherapy Systems *Clin. Oncol.* **30** 686–91

Lundman J A, Bylund M, Garpebring A, Thellenberg Karlsson C and Nyholm T 2017 Patient-induced susceptibility effects simulation in magnetic resonance imaging *Phys. Imaging Radiat. Oncol.* **1** 41–5 Online: http://dx.doi.org/10.1016/j.phro.2017.02.004

Macmillan Cancer Support 2015 *The burden of cancer and other long-term conditions* Online: https://www.macmillan.org.uk/documents/press/cancerandotherlong-termconditions.pdf

Mah D, Steckner M, Palacio E, Mitra R, Richardson T and Hanks G E 2002 Characteristics and quality assurance of a dedicated open 0.23 T MRI for radiation therapy simulation *Med. Phys.* **29** 2541–7

Maintz J B A and Viergever M A 1998 A survey of medical image registration *Med. Image Anal.* **2** 1–36

Masselli G and Gualdi G 2012 MR imaging of the small bowel *Radiology* **264** 333–48

Matakos A, Balter J M and Cao Y 2017 A Robust Method for Estimating B0 Inhomogeneity Field in the Liver by Mitigating Fat Signals and Phase-Wrapping *Tomogr. (Ann Arbor, Mich.)* **3** 79–88

McRobbie D and Semple S 2017 *Quality Control and Artefacts in Magnetic Resonance Imaging - IPEM Report 112*

McWilliam A, Rowland B and van Herk M 2018 The Challenges of Using MRI During Radiotherapy *Clin. Oncol.* **30** 680–5

MHRA 2015 *Safety Guidelines for Magnetic Resonance Imaging Equipment in Clinical Use* Online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/476931/MRI_guidance_2015_-_4-02d1.pdf

Mizowaki T, Nagata Y, Okajima K, Kokubo M, Negoro Y, Araki N and Hiraoka M 2000 Reproducibility of geometric distortion in magnetic resonance imaging based on phantom studies *Radiother. Oncol.* **57** 237–42

NHS England 2018 Radiotherapy Services Specification Online: https://www.engage.england.nhs.uk/consultation/radiotherapy-service-specification-consultation/user_uploads/radiotherapy-service-specification.pdf

Patel I 2018 *Physics Aspects of Quality Control in Radiotherapy - IPEM Report 81, 2nd edition*

Pathmanathan A U, Schmidt M A, Brand D H, Kousi E, van As N J and Tree A C 2019 Improving fiducial and prostate capsule visualization for radiotherapy planning using MRI *J. Appl. Clin. Med. Phys.* **20** 27–36

Paulson E, Cao Y, Best L, Herbert T, Sohlin M, Rai R, Ménard C and Roberge D 2018 *MR-integrated Workflows in Radiation Therapy for MAGNETOM Systems* Online: https://www.siemens-healthineers.com/magnetic-resonance-imaging/magnetom-world/hot-topics/mri-in-radiation-

therapy#Protocols

Paulson E S 2016 How-I-Do-It: Comprehensive RT-Specific QA for MRI Simulation *Siemens - MReadings MR RT - Second Ext. Ed.* 62–4 Online: https://static.healthcare.siemens.com/siemens_hwem-hwem_ssxa_websites-context-root/wcm/idc/groups/public/@global/@imaging/@mri/documents/download/mda2/mjex/~edisp/mr_mreadings-in-rt_2nd-extended-edition-03335135.pdf

Paulson E S, Crijns S P M, Keller B M, Wang J, Schmidt M A, Coutts G and van der Heide U A 2016 Consensus opinion on MRI simulation for external beam radiation treatment planning *Radiother. Oncol.* **121** 187–92 Online: http://dx.doi.org/10.1016/j.radonc.2016.09.018

Paulson E S, Erickson B, Schultz C and Allen Li X 2015 Comprehensive MRI simulation methodology using a dedicated MRI scanner in radiation oncology for external beam radiation treatment planning *Med. Phys.* **42** 28–39 Online: https://aapm.onlinelibrary.wiley.com/doi/abs/10.1118/1.4896096

Petersch B, Bogner J, Fransson A, Lorang T and Pötter R 2004 Effects of geometric distortion in 0.2 T MRI on radiotherapy treatment planning of prostate cancer *Radiother. Oncol.* **71** 55–64

Pipe J G 1999 Motion correction with PROPELLER MRI: Application to head motion and free-breathing cardiac imaging *Magn. Reson. Med.* **42** 963–9

Port J D and Pomper M G 2000 Quantification and minimization of magnetic susceptibility artifacts on GRE images *J. Comput. Assist. Tomogr.* **24** 958–64

Rai R, Kumar S, Batumalai V, Elwadia D, Ohanessian L, Juresic E, Cassapi L, Vinod S K, Holloway L, Keall P J and Liney G P 2017 The integration of MRI in radiation therapy: collaboration of radiographers and radiation therapists *J. Med. Radiat. Sci.* **64** 61–8

Ranta I, Kemppainen R, Keyriläinen J, Suilamo S, Heikkinen S, Kapanen M and Saunavaara J 2019 Quality assurance measurements of geometric accuracy for magnetic resonance imaging-based radiotherapy treatment planning *Phys. Medica* **62** 47–52

RCR 2019 *Guidance on gadolinium-based contrast agent administration to adult patients* Online: https://www.rcr.ac.uk/system/files/publication/field_publication_files/bfcr193-gadolinium-based-contrast-agent-adult-patients.pdf

Schmidt M A, Panek R, Colgan R, Hughes J, Sohaib A, Saran F, Murray J, Bernard J, Revell P, Nittka M,

Leach M O and Hansen V N 2016 Slice Encoding for Metal Artefact Correction in magnetic resonance imaging examinations for radiotherapy planning *Radiother. Oncol.* **120** 356–62 Online: http://dx.doi.org/10.1016/j.radonc.2016.05.004

Schmidt M A and Payne G S 2015 Radiotherapy planning using MRI *Phys. Med. Biol.* **60** R323–61 Online: https://www.ncbi.nlm.nih.gov/pubmed/26509844

Schmidt M A, Wells E J, Davison K, Riddell A M, Welsh L and Saran F 2017 Stereotactic radiosurgery planning of vestibular schwannomas: Is MRI at 3 Tesla geometrically accurate *Med. Phys.* **44** 375–81

SCoR 2019 *Safety in Magnetic Resonance Imaging* (London) Online: ISBN: 978-1-909802-31-5

SCoR 2020 *MRI Guided Radiotherapy* (London) Online: ISBN 978-1-909802-48-3

Seppenwoolde Y, Shirato H, Kei Kitamura, Shimizu S, Herk M Van, Lebesque J and Kazuo Miyasaka 2002 Precise and Real-Time Measurement of 3D Tumor Motion in *Int J Radiat Oncol Biol Phys* **53** 822–34 Online: https://ac.els-cdn.com/S0360301602028031/1-s2.0-S0360301602028031-main.pdf?_tid=fcafcbed-7f00-44d5-9f3d-d7617a229fcb&acdnat=1537233756_f982990fcd390e2d298b7471a8486527

Shellock F G, Woods T O and Crues J V. 2009 MR labeling information for implants and devices: Explanation of terminology *Radiology* **253** 26–30

Speight R, Schmidt M A, Liney G P, Johnstone R, Eccles C, George B, Henry A and McCallum H M 2019 IPEM Topical Report: A 2018 IPEM survey of MRI use for external beam radiotherapy treatment planning in the UK *Phys. Med. Biol.* **64** 175021 Online: iopscience.iop.org/article/10.1088/1361-6560/ab2c7c

Stanescu T, Wachowicz K and Jaffray D A 2012 Characterization of tissue magnetic susceptibility-induced distortions for MRIgRT *Med. Phys.* **39** 7185–93

Stemkens B, Paulson E S and Tijssen R H N 2018 Nuts and bolts of 4D-MRI for radiotherapy *Phys. Med. Biol.* **63** 23 Online: http://iopscience.iop.org/article/10.1088/1361-6560/aae56d/meta

Tijssen R H N, Philippens M E P, Paulson E S, Glitzner M, Chugh B, Wetscherek A, Dubec M, Wang J and van der Heide U A 2019 MRI commissioning of 1.5T MR-linac systems – a multi-institutional study *Radiother. Oncol.* **132** 114–20 Online: https://doi.org/10.1016/j.radonc.2018.12.011

Wang H, Balter J and Cao Y 2013 Patient-induced susceptibility effect on geometric distortion of clinical brain MRI for radiation treatment planning on a 3T scanner *Phys. Med. Biol.* **58** 465

Westbrook C 2017 Opening the debate on MRI practitioner education – Is there a need for change? *Radiography* **23** S70–4

Wood R, Bassett K, Foerster V, Spry C and Tong L 2011 1.5 Tesla Magnetic Resonance Imaging Scanners Compared with 3.0 Tesla Magnetic Resonance Imaging Scanners: Systematic Review of Clinical Effectiveness [Internet]. *Ottawa Can. Agency Drugs Technol. Heal. 2011 (CADTH Rapid Response Report)*

Xing A, Holloway L and Arumugam S 2016 Commissioning and quality control of a dedicated wide bore 3T MRI simulator for radiotherapy planning *Int. J. Cancer Ther. Oncol.* **4** 421