MRI for Radiotherapy

Planning, Delivery, and Response Assessment

Gary Liney
Uulke van der Heide
Editors

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MRI in Radiotherapy: Introduction

As radiotherapy delivery has increased in terms of conformity and precision, so too has the need for accurate imaging in order to plan these treatments. MRI has much to offer as the imaging technique of choice; the soft-tissue contrast provides exquisite visualisation of both the tumour target and organs at risk improving the simulation and planning; it allows functional parameters to be measured in the same examination providing physiological information about tumour response or tissue toxicity. Furthermore, because MRI is a nonionising modality, it lends itself to repeat imaging offering the prospect of using this information frequently during treatment and adapting the radiation dose as needed on an individual patient basis.

The benefits of MRI for radiotherapy were first recognised as early as the 1980s, and subsequent work went on to quantify geometrical accuracy and demonstrate bulk density correction for MR-only planning. However, clinical practice changed little over the ensuing decades; CT remained the gold standard modality, and the perceived difficulties associated with MRI persisted. There are perhaps two good reasons for this; the fields of radiotherapy and MRI are large and different enough for these subjects to remain distinct in terms of training and education; access to MRI is a perennial problem and is typically limited to the ad hoc use of radiology scanners further restricting development for all but the larger research centres. These factors have all too often been a barrier to implementing MRI routinely in the clinic.

Nevertheless, in recent years, there has been a drive to see 'MR in RT' become a specialism in its own right, and there are a couple of initiatives worthy of mention. In 2010, ESTRO introduced its 'imaging for physicists' course with a focus on MRI. This course is now in its tenth year and remains consistently popular all across Europe. A second big step has been the creation of the dedicated 'MR in RT Symposium'. What began as a local workshop between James Balter and a few colleagues in 2013 has since grown into an important fixture on the international calendar. The Symposium has been held across the USA, Europe and Australia with attendance continuing to rise each year.

At the same time, MRI vendors have recognised this growing interest and developed RT solutions for treatment-position imaging and MR-only planning. More importantly, radiotherapy centres have begun installing their own MRI systems. Throughout all of this, there has been the exciting development of hybrid MRI treatment devices. We are now starting to see the long-term follow-up from the early pioneering MRI-cobalt machines with results

showing the benefit of MR-guided adaptation. In 2017, the first ever patients were treated on commercial MRI-Linac systems.

Photograph taken during the 6th International MR in RT Symposium in Utrecht July 2018, featuring some of the book contributors: (left to right) Richard Speight, Neelam Tyagi, Robba Rai, Brad Oborn, Gary Liney, Uulke van der Heide, Michael Barton, Rob Tijssen and Teo Stanescu

The emergence of MR in RT is also clear through an increasing body of published literature. Journals in the field of radiation oncology are including more and more MRI articles, with both a technical and clinical scope. While for some new developments, such as clinical treatments on MR-guided systems, experience is still limited, in other areas, the field is maturing, and a consensus on utilisation is building. Nonetheless, a comprehensive overview of the issues and opportunities of MRI in radiotherapy is still lacking. Against this backdrop, the time seemed overdue for writing (or rather editing!) such a textbook. In doing so, we have brought together colleagues who are recognised experts in this field, all of whom actively participate in the professional development of 'MR in RT'. Each of the authors represent the multiple disciplines involved in our field, namely, physics, radiography and oncology, and the text is aimed at an equally wide audience.

The book is divided into five parts showing how MRI is being used in the clinic in a logical progression from simulation through to real-time guidance. Part I begins with treatment planning, and Chap. 1 covers image acquisition from patient set-up to image protocols. MRI registration with CT is then described followed by quality assurance with a particular emphasis on geometric distortion. The final chapter in this part goes through the clinical sites of importance. Part II deals with the role of MRI as a tool during treatment; functional imaging techniques are introduced, and then studies in response assessment are considered. This part concludes with the use of MRI for motion management. MR-only radiotherapy is the focus of Part III, and both the dosimetry requirements and the techniques used to replace CT are covered here. The book then moves into the newest area of development, namely, in-room guidance; the chapters here review the first results obtained on ViewRay's cobalt system and go on to discuss the technical challenges and current status of MRI-Linac systems. To conclude, there is a discussion on the future roles for MRI with one eye towards proton therapy.

We hope you agree that the end result has been an outstanding first edition of what is sure to become a must-read in the field of MRI in radiotherapy. We would like to end by acknowledging each of the contributing authors for their time and commitment to this project and to Springer for backing the initial proposal.

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About the Editors

Gary Liney is the senior medical physicist at the Ingham Institute for Applied Medical Research and Liverpool Cancer Therapy Centre, Sydney, Australia. He is providing the scientific lead into the MRI-simulator and MRI-Linac programs at Liverpool. Gary is a recognised expert in the use and integration of MRI techniques into radiotherapy planning and published over 70 scientific papers and three textbooks. He has taught on the ESTRO 'imaging for physicists' course since its inception in 2010. He is currently leading the investigations on the Australian phase 2 MRI-Linac system using a dedicated split bore open magnet to provide real-time MRI-guided therapy.

Uulke van der Heide works as a medical physicist and group leader at the Netherlands Cancer Institute in Amsterdam, the Netherlands. He holds a chair as professor of imaging technology in radiotherapy at the Leiden University. He was the course director on the ESTRO 'imaging for physicists' course until 2017. His research group works on the improvement of target definition in radiotherapy by application of MRI and the development and validation of quantitative imaging methods for tumour characterisation for radiotherapy dose painting. He further leads the MR-guided radiotherapy program at the Netherlands Cancer Institute.

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Part I

MRI for Planning

1 Implementation and Acquisition Protocols

Rob H. N. Tijssen, Eric S. Paulson, and Robba Rai

1.1 Introduction

The past decade has shown that magnetic resonance imaging (MRI) is increasingly being utilised in the radiation therapy setting not only for radiation therapy planning (RTP) purposes but also in assessment of treatment response and online MR-guidance on hybrid MR-linac systems. Because of the ever-growing use of MRI in radiation therapy, it is inevitable that more departments will be looking to move forward and use MRI as a complementary imaging modality in their RTP protocols or as a sole imaging modality in MR-only workflows.

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There are many requirements for the effective utilisation of MRI in radiation therapy including screening and safe scanning of common devices used in oncology, reproducible and comfortable setup for patients, and specific scanning protocols required to meet the needs for RTP. Additional education and training will be required to ensure that centres harness the full potential of MRI.

1.2 Implementing MRI for Treatment Planning

1.2.1 Site Planning and Installation

1.2.1.1 Room Design

Modern MRI scanners are designed to have a small footprint. However, there are various considerations that need to be accounted for when setting up an MRI suite in radiation therapy including shielding, equipment storage, and room safety.

An MRI suite requires (active) shielding to ensure that the magnetic fringe field does not encroach on sensitive equipment that may be in the vicinity of the area such as linear accelerators. In addition to shielding the magnetic fringe field of the scanner, the room needs to be shielded against radio frequency (RF) as RF from external sources distorts the MR signal and the RF produced by the scanner may interfere with other surrounding medical devices. Finally, building vibrations may introduce image artefacts.

Vibration levels in the scanner room need to be low and comply with the system's requirements provided by the vendor.

A modern MRI requires a lot of equipment such as gradient and radio-frequency cabinets, power cabinets, helium compressor, and a chiller. These system components are stored in separate cabinets and must be accessible to medical physics and engineering staff for routine servicing and preventative maintenance. Access to these system components must be restricted to prevent tampering by the public and untrained staff.

The American College of Radiology Expert Panel on MRI safety (Kanal et al. 2013) has defined geographical MRI safety zones. The MRI control area is included in Zone III, and access to Zone III should be restricted to MRI-trained staff only (see Sect. 1.2.3.1). Various doors can be implemented that lead to the control room such as a single sliding door that can only be accessed by patients under the supervision of MRI-trained staff. All members of the general public and untrained oncology staff should not have access to Zone III.

Zone IV is defined as the MRI scanner room. Some departments with dedicated MRI simulators in oncology will include an obvious demarcation in their floor design to indicate where the 30 gauss fringe field line is in relation to the MRI (Fig. 1.1) (Xing et al. 2016).

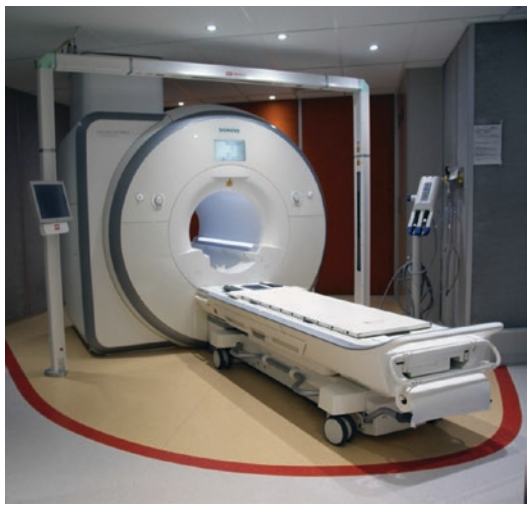

Fig. 1.1 Example of a MRI simulator with 30 G line marked on the floor

1.2.1.2 RT Immobilisation Equipment

A major difference between radiation therapy and radiology is the heavy use of immobilisation equipment. Prior to using RT immobilisation devices in the MRI room, equipment needs to be compatible for both safety and image quality. It is important to note that carbon fibre is often used in RT equipment and this has the potential to cause RF heating and attenuation of MR signal (Juresic et al. 2018; Jafar et al. 2016). The MRI compatibility of devices and equipment used in Zone IV should be designated with MRI safety labels (e.g. MR safe, MR conditional, MR unsafe). However, in the event that an unlabelled device or equipment is to be used, in-house testing for MRI compatibility should be performed prior to releasing the device for clinical use.

Immobilization devices should also be tested to ensure that they fit within the MRI bore. RT immobilisation devices are traditionally designed for large bore CT simulators and open table linear accelerators, so ensuring these devices are compatible with a MRI closed-bore scanner is essential.

It is also important to note that RT immobilisation equipment can have a severe impact on the overall image quality of MRI simulation scans and this should be quantitatively assessed with phantom studies. This will be addressed in further detail in Sect. 1.2.4.1.

1.2.2 Training

To introduce an MRI into the radiation therapy workflow in a safe and effective manner, training is essential. MR imaging requires specialised expertise, which is very distinct from kV-based imaging. Training is a multidisciplinary effort in which the radiation technologists (RTT), as well as the radiation oncologists (RTO), and medical physicists (MP) must be involved. The obvious common ground here is MRI safety as discussed below, but also the quality of the images is something that needs to be reviewed periodically in order to assure that the image quality remains of high standard. Continuing education is extremely important as imaging protocols and

the use of the images (e.g. MR-only and 4D-MRI) continue to evolve. A good collaboration with radiology is therefore extremely beneficial when setting up an MRI for RT.

For departments that share resources with radiology, the collaboration is prerequisite as the logistics need to be aligned. Scan slots for radiotherapy, for example, need to be longer than a regular diagnostic scan slot as patient setup takes more time (e.g. due to accurate laser alignment and the use of positioning devices). Even when a radiation therapy department owns dedicated MRI-RT systems, it is advisable to maintain a close collaboration with radiology. The experienced radiology staff may contribute in setting up safety procedures and assist in protocol development and quality assurance. Furthermore, the established relationship between the radiology department and the MRI vendor can be very useful when service is required or when purchasing new equipment.

1.2.3 MR Safety

1.2.3.1 Safety Certification and Scanner Access

Departmental safety training for all staff in oncology will ensure that staff who require access to Zones III or IV are made aware of the most recent information regarding both international and local safety standards. Access to the MRI room should be strictly monitored, preferably with smart card or key access only granted to staff that are abreast of MRI safety standards. The American College of Radiology recommends that all individuals working in Zone III should have successfully attended MRI safety lectures and live presentations and that these should be repeated annually and documented to confirm ongoing educational efforts (Kanal et al. 2013).

1.2.3.2 Safety Screening

All staff involved in the day-to-day scanning of patients in MRI departments should be screened prior to working in this section of the department. There are many examples of MRI screening questionnaires available, including online sources (Shellock 2017a) or adapted versions from established radiology departments. The screening form should be completed and reviewed by the Principal Physicist or MRI safety officer in charge of the area to ensure staff are safe to work in the area prior to commencement.

Patients should complete a safety questionnaire prior to MRI simulation, to assess their suitability for the procedure and detect any potential contraindications to the MRI. This should be completed with a trained MRI technician or the RTO at time of consultation for radiation therapy. The screening questionnaire should be completed with ample time to review and ensure any potential devices that the patient may have implanted are checked for compatibility with the MRI simulator.

For patients with implantable medical devices, the Medicines and Healthcare products Regulatory Agency (MHRA) recommends that a risk assessment should be undertaken with involvement of a multidisciplinary team including the MR responsible person (radiation therapist or diagnostic MRI technician), MR safety expert (MRI Physicist) and relevant specialist clinician (radiologist or oncologist) (Medicines and Healthcare products Regulatory Agency (MHRA) 2007). They advise that the following should be considered:

- Alternative imaging modalities.
- Imaging on an MRI with a lower static and/or gradient field.
- Advise from implant manufacturer.
- Locally available advice and recommendation from professional organisation.
- Published evidence of scanning the device.
- Available data about the device.
- Assessment of MRI artefacts arising from the device.
- MRI device parameters.

The decision to image a patient with an implantable medical device should be decided by local departmental protocol based on recommendations and advice from your local governing professional organisation.

1.2.3.3 Vascular Devices In Situ

Patients undergoing concurrent chemoradiotherapy (CRT) may have vascular devices inserted such as port-a-caths (ports) and peripherally inserted central catheters (PICCs) at time of their MR imaging. Ports and PICCs are common in situ vascular devices used in oncology with specific safety restrictions for scanning in MRI. Patients with these devices should be scanned under particular conditions, and the technician staff needs to ensure that specific absorption rate (SAR) levels are strictly controlled.

Considerations

Prior to MR scanning, the referring physician is responsible for managing the patient relative to the use of MRI and ensures that the following information regarding the device is considered:

- *Compatibility of device at specific field strength*.
  Before a patient with a vascular device is scanned in the MRI, the MRI compatibility of the device should be confirmed for the field strength of the scanner.
- *Safe spatial gradient field recommendations as defined by the device manufacturer*.
  Individual scanners will have a unique spatial gradient field map (i.e. change in B0 field with proximity to bore), and this should be used as a guide to determine where the strongest spatial gradient field is in relation to the device.
- *MRI-related heating using normal and first level SAR limits*.
  Scan modes typically include normal (2 W/kg) and first level (3 W/kg) modes (vendor neutral). The modes determine the tolerance for SAR levels during a single examination. Manufacturers of these devices will usually include safe scan mode recommendations based on their own independent testing, and this should be followed in the clinical setting to ensure safe scanning of patients with these devices.

1.2.3.4 Cardiac Pacemakers and Defibrillators

Cardiac pacemakers and implantable cardioverter defibrillators (ICDs) are devices implanted into patients to help control abnormal heart rhythms by using electrical pulses to ensure the heart beats at a normal rate. For patients with these devices, the MRI compatibility of the devices must also be confirmed with manufacturer guidelines prior to the MR simulation exam.

Legacy pacemaker's and ICD devices have traditionally been contraindicated in MRI as the risks to the patient outweigh the benefits. Potential problems include (Shellock 2017b):

- Movement of the device or leads.
- Potential adverse modification of function of the device.
- Unavoidable triggering or activation of the device.
- Heating in the leads.
- Induced currents in the leads.
- Electromagnetic interferences.

These effects often pertain to older cardiac pacemakers and ICDs; consequently patients with devices implanted prior to the year 2000 are at greatest risk during MRI scanning (Ahmed et al. 2013). Therefore, the risk versus benefits need to be weighed when considering MRI for patients with older cardiac pacemakers and ICDs, even if they are safe for radiation therapy. Some manufacturers of modern cardiac pacemakers and ICDs (post-2000) have developed MRI-conditional devices that can be scanned under particular conditions (e.g. 1.5 T or less). Manufacturer guidelines should be followed strictly to ensure that the patient is safe during the MRI exam. This includes monitoring the performance and functionality of the device before, during and after scanning.

It is also important to note that patients who have MRI-compatible devices must also have the leads checked for compatibility. Some leads may not be MRI compatible and can have potential to heat or induce current during the MRI scanning process.

1.2.3.5 Safe Administration of Gadolinium

Gadolinium-based contrast agents (GBCAs) are commonly used to enhance T_1 images in areas

of abnormality by shortening the T_1 relaxation properties of the local microenvironment. These agents are filtered through the kidneys. There are two types of GBCAs based on their chemical structure: linear and macrocyclic. Mounting evidence demonstrates that linear GBCAs are retained in the body longer compared to macrocyclic GBCAs, with higher levels of gadolinium remaining in the body after administration of linear GBCAs (U.S. Food and Drug Administration 2017). Both the FDA and European Medicines Agency recommend the suspension of linear GBCAs except for liver-specific agents such as gadoxetic and gadobenic acids as they are taken up in the liver only and its benefits outweigh the risks.

Prior to administration of contrast, appropriate blood analysis including eGFR (estimated glomerular filtration rate) and creatinine should be assessed in the patient to ensure that kidney function is optimal for filtration of GBCAs' post administration. The patient should be counselled on possible side effects of gadolinium based on local departmental guidelines.

Clinically, the usefulness of contrast-enhanced MR imaging should be weighed against contrast-enhanced CT. There is little evidence in the literature to suggest the optimal waiting time between administration of iodine and GBCAs. However, Golder et al. recommend that "it is advisable to wait longer than one day to perform the second iodine or gadolinium-enhanced test" (Golder 2012). Although GBCAs can be safely administered within a short period of iodinated contrast, the burden to the patient having double contrast within a short period of time should be considered in the planning process.

1.2.4 Integrate MRI into the RTP Workflow

MRI datasets can be used for both registrations to CT to assist in tumour and organs at risk (OAR) delineation in radiotherapy planning and also to be used solely for the purposes of MR-only planning.

Scans acquired in the radiology setting are used to investigate where the disease is and deduce a differential diagnosis based on its imaging features (Devic 2012). Although diagnostic acquired MRI does not consider the treatment position of the patient, these datasets may still be useful for registration to CT to assist with planning so long as there is an indicator of the geometric fidelity of the diagnostic MR images.

The following section will address various scenarios where MRI can be used in conjunction with CT and can be used as a guide for the effective use of MRI in individualised clinical settings based on Fig. 1.2.

1.2.4.1 MRI Acquired in Radiotherapy Position

Immobilisation devices are used to minimise the risk of movement and improve overall reproducibility for fractionated treatments (Devic 2012). Figure 1.3a shows various immobilisation devices used for radiation therapy setup including a flat table overlay with indexing, thermoplastic mask secured to the flat table as well as knee and ankle fixation devices.

For imaging in the treatment position, there are a number of considerations when using RT immobilisation equipment including:

- Flat table overlay.
  - In-house built tables as well as commercially available devices should be tested to ensure the materials do not cause any heating.
  - The thickness of the table should be measured to assess signal-to-noise ratio (SNR) loss resulting from the increased distance between the patient and the integrated RF coils under the bed.
- Thermoplastic masks, knee, and ankle fixation.
  - All devices should be tested to ensure the materials do not cause any heating and are compatible with flat table overlay and indexing system.

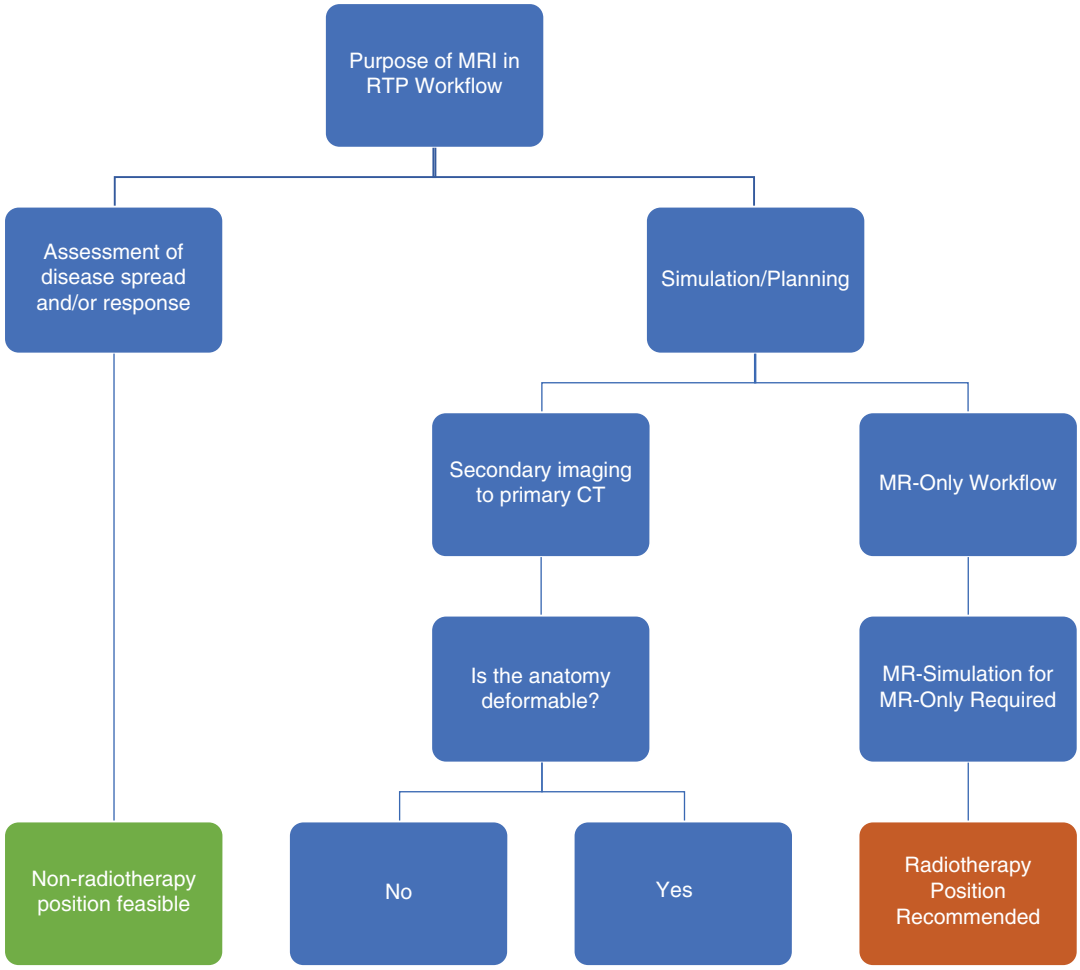

Fig. 1.2 Guide for the use of different imaging positions in the RTP workflow

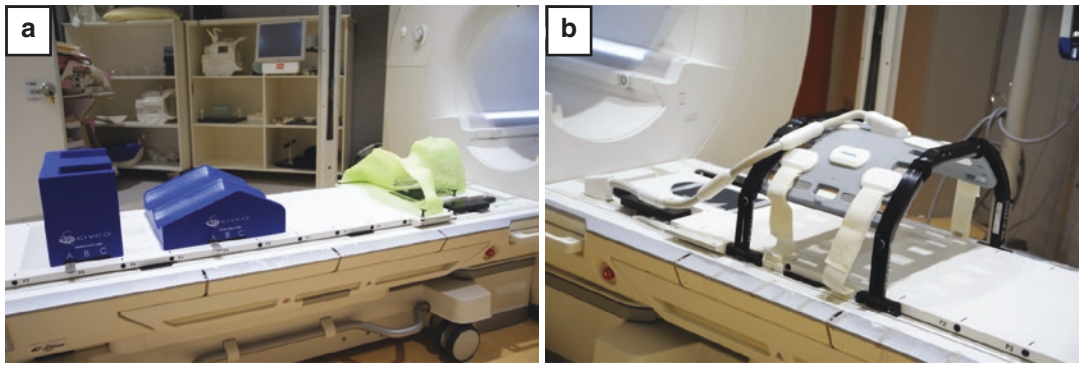

Fig. 1.3 Various RT-specific immobilisation devices that can be used in MRI for reproducible setup to improve registration to CT in the planning process including (**a**) thermoplastic masks, flat table overlays, and knee and ankle fixation devices and (**b**) RF coils attached to bridges to minimise deformation of external body contours

- RF coil bridges.
  - Similar to the flat table overlay, the addition of RF coil bridges (Fig. 1.3b) may increase the distance between the region being scanned and the coil elements. Imaging protocols may have to be adjusted accordingly.

Figure 1.4 shows an example of a head and neck setup using a thermoplastic mask and vacuum bag. These setups will often require the use of flexible coils arranged to cover the anatomy of interest. Signal to noise ratio should be taken into consideration with individual coil arrangements and sequences required for planning.

In the case that the MRI will be used as a secondary imaging modality to the primary CT, coils can be placed directly over the patient anatomy to improve the overall image quality as long as the region of interest is not deformed by the weight of the coil.

External lasers can be useful in aligning patients to reproduce their CT simulation position. In complex setups such as extremities (Fig. 1.5a), care should be taken to try to position target volumes as close to MR isocentre as possible. This may require the patient be offset laterally in the MRI bore (Fig. 1.5b) but will reduce residual geometric distortions. For modern MRI scanners where closed-bore systems are becoming the norm, the use of RT immobilisation devices may pose positioning challenges due to size restrictions, and this should be taken into consideration for radiotherapy planning positions.

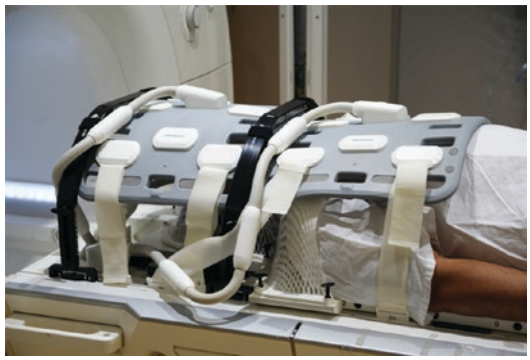

Fig. 1.4 Example of a head and neck setup with the patient immobilised using a thermoplastic mask and vacuum bag

1.2.4.2 MRI Acquired in Non-radiotherapy Position

For anatomical regions where deformation and variation in position of targets and OARs are prevalent, such as the abdomen, head, and neck, MR images acquired with a non-radiotherapy position may be difficult to co-register to planning CT images for RTP. In regions where deformation of the anatomy is not an issue, such as the brain, scans acquired with diagnostic RF coils and non-radiotherapy position may still be useful for registration to CT (Fig. 1.6). These aspects of image registration will be covered in Chap. 2.

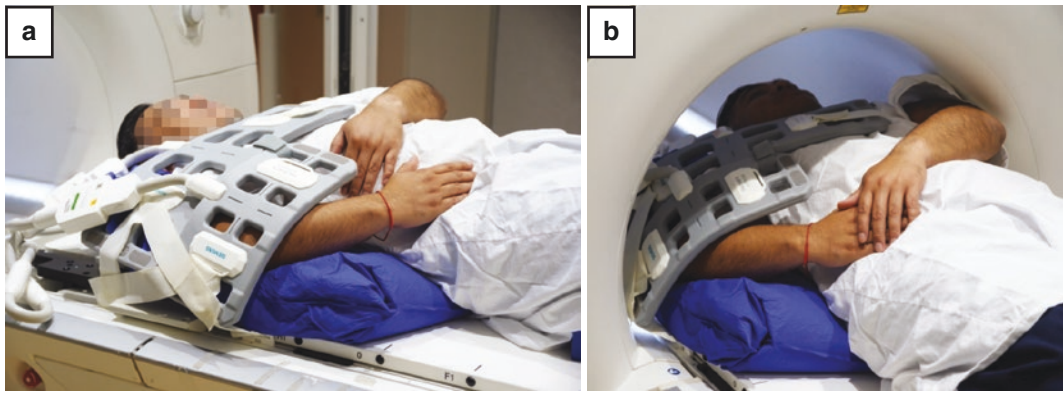

Fig. 1.5 Example of upper extremity setup using a tailored coil arrangement (**a**). The participants was offset laterally to position the arm closer to the isocentre of the MRI to improve image quality (**b**)

Fig. 1.6 Positioning for brain imaging using a dedicated head and neck coil in a diagnostic MRI setup

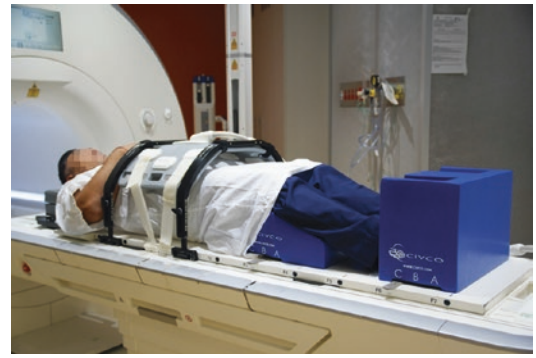

Fig. 1.7 Example of a pelvis setup in the radiotherapy position. The coil is suspended above the subject's pelvis and secured with Velcro to coil bridges to minimise deformation of the external body contour

The advantages of using a non-radiotherapy position with dedicated anatomical coils include (1) improvement in image quality due to increased SNR, (2) greater comfort for the patient as immobilisation devices do not need to be used, and (3) minimisation of the risk of motion artefacts.

1.2.4.3 MR-Only Planning

MR-only planning workflows require specific sequences for synthetic CT generation and are discussed in detail in Chaps. 8 and 9.

In regard to setup, patients should be positioned in their treatment position, ideally in an MRI simulator or diagnostic department equipped with RT-specific immobilisation, external laser positioning, and marking system for alignment. In comparison to MRI acquisition as a complimentary modality to CT, care needs to be taken when placing RF coils over the anatomy of interest. Coils should not be directly placed over the anatomical regions as any added weight from the coil on the anatomy can deform the external body contours, leading to a potential variation in dose (Fig. 1.7).

High-resolution large field-of-view imaging is a prerequisite for MR-only workflows, and coverage of the entire treatment volume is essential. For anatomical sites in which fiducial markers will be used for registration, such as in prostate, MRI examinations should include sequences that will assist with the visualisation of these markers such as gradient echo or proton density-weighted turbo spin echo. These sequences will enhance the paramagnetic susceptibility effects of these fiducials as they are often made of gold or polymer with a stainless steel core.

1.3 Acquisition Protocols for RTP

MRI for RTP requires dedicated imaging protocols to ensure high imaging standards for RTP including high resolution with minimal geometric distortions. This section covers the basic MR theory needed for protocol development and will detail recommended parameters for MR simulation for RTP.

1.3.1 Image Contrast

MRI is an extremely versatile imaging modality. Unlike any other modality, MRI offers a vast array of image contrasts. A typical exam for radiotherapy treatment planning therefore includes a number of contrasts that offer complementary information.

1.3.1.1 Anatomical Imaging: T1 and T2 Contrast

The most fundamental properties that MRI makes use of are T1 and T2 relaxation (Table 1.1) (De Bazelaire et al. 2004; Stanisz et al. 2005; Wansapura et al. 1999). Since the relaxation phenomenon is described in much detail in all textbooks on MRI physics (King et al. 2004; Haacke

Table 1.1 T1 and T2 relaxation times at 1.5 and 3 T

	1.5 T		3 T	
Tissue	T1 (ms)	T2 (ms)	T1 (ms)	T2 (ms)
Subcutaneous fat	343	58	382	68
Liver	586	46	809	34
Pancreas	584	46	725	43
Spleen	1057	79	1328	61
Muscle	856	27	898	29
Prostate	1317	88	1597	74
White matter	600	80	830	80
Grey matter	900	100	1330	110
CSF	3500	2200	4000	2000

et al. 2014; McRobbie et al. 2006), we suffice here by reminding the reader that T1 relaxation describes the realignment of the proton spins towards the direction of the magnetic field, while T2 relaxation refers to the loss of coherence in transverse magnetization. The different tissues in the human body all have their own characteristic T1 and T2 relaxation rates (Table 1.1). These differences in relaxation are at the basis of contrast generation. Contrast is generated by setting the RF flip angle and the sequence timing parameters in such a way that differences in signal intensity between species with different relaxation parameters are maximized. Relaxation rates at 3 T are different than those at 1.5 T, so the sequence parameters required to generate optimal contrast will also vary for the different field strengths.

T1 Contrast

The timing parameter that determines T1 contrast is the repetition time (TR). By increasing the TR, more time is allowed for the longitudinal magnetization (M_L) to recover to its equilibrium state. The amount of longitudinal magnetization determines the amount of signal that is available for the next readout. Figure 1.8a shows the longitudinal relaxation after a 90° RF pulse. It takes about five times the T1 for the longitudinal magnetization to fully recover. By choosing a shorter TR (denoted by the dotted line), the magnetization will only partly recover, but, more importantly, the amount of recovery will be different between different tissues. Tissues with a short T1 (e.g. liver tissue) will thus provide higher signal than tissues with a long T1 (e.g. muscle or CSF). T1 contrast is optimized by finding the right combination of RF flip angle and TR. Additionally, T1 weighting can be amplified by placing an inversion pulse in front of the sequence, which inverts the longitudinal magnetization of both species to be antiparallel with the main magnetic field (Fig. 1.8c). By carefully choosing the inversion time (TI: the time between the inversion pulse and the regular excitation pulse), one could null (i.e. suppress) the signal of one of the two species as described in more detail in Sect. 1.3.1.2.

T2 Contrast

T2 contrast is determined by the echo time (TE), which is the time between the RF excitation pulse and the actual collection of the data. Immediately after the RF pulse, the spins start to dephase, which causes a reduction of the transverse magnetization (M_T), and thus signal (Fig. 1.8b). The rate of dephasing is different for each tissue and determined by the different T2 values. Again, the contrast is optimized by choosing the timing parameter (in this case the TE) in such a way that the difference between species A and B is maximized. For sequences that acquire multiple lines of k-space per TR, for example, turbo spin echo (TSE), the TE is defined as the time at which the central line in k-space is collected.

The Effect of Gadolinium

Because of its paramagnetic properties, gadolinium shortens both the T1 and the T2 relaxation times. Which effect dominates depends on the baseline relaxation times of the tissue under investigation and gadolinium concentration, but for most anatomical imaging, gadolinium is administered to enhance T1 contrast. By shortening the T1 of the nearby hydrogen protons, the signal is enhanced in areas where the contrast agent is present. Especially for brain tumours that have leaky vessels, contrast-enhanced imaging is very useful to distinguish between active tumour tissue and the necrotic core. An example showing the effect of contrast enhancement is shown by Fig. 1.8d.

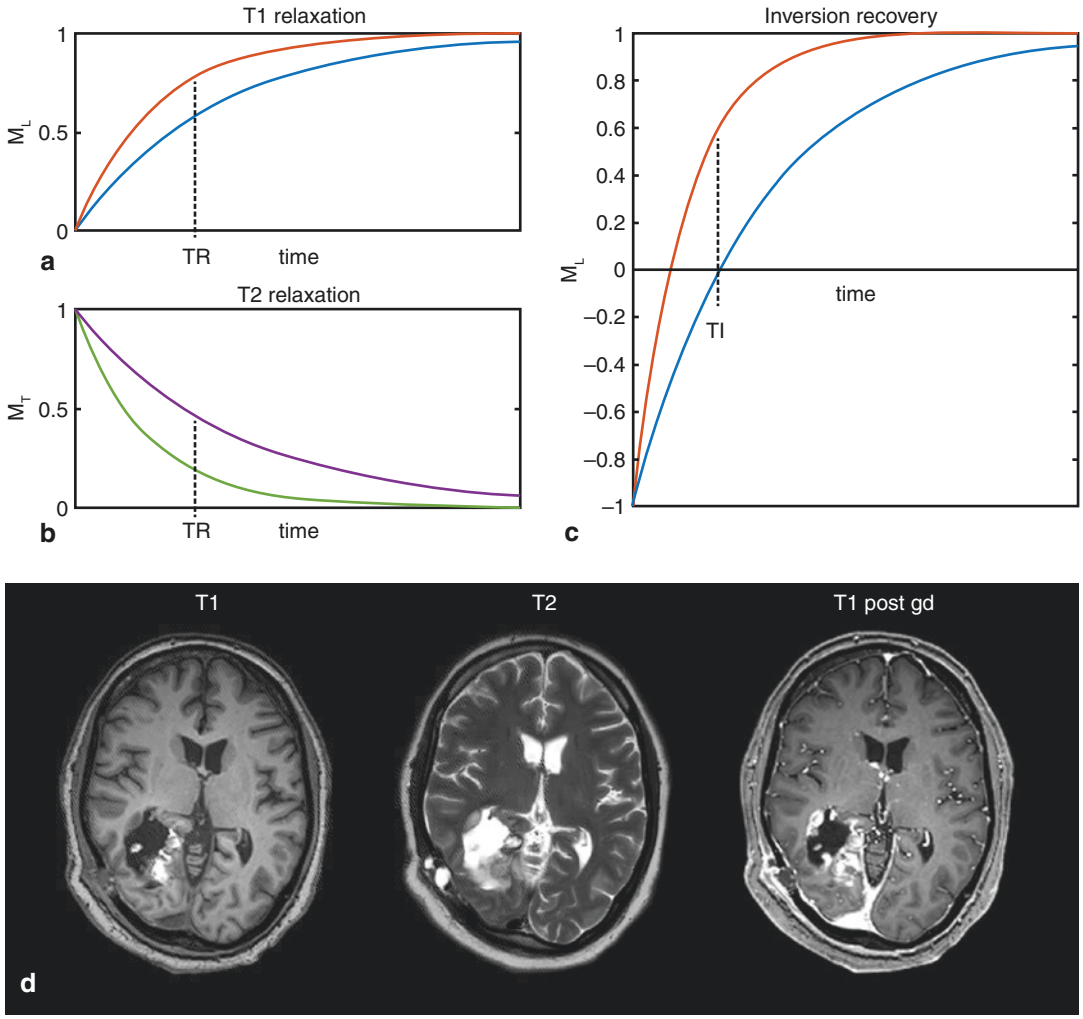

Fig. 1.8 Panels **a**–**c** show T1 and T2 relaxation curves with optimal timing parameters (TR, TE, and TI) denoted by the dotted lines. Panel **a** shows the longitudinal relaxation after a 90° RF pulse, while panel **c** simulates a 180° inversion pulse. Panel **d** shows examples of T1-weighted, T2-weighted, and post contrast T1-weighted images

1.3.1.2 Anatomical Imaging: Fat Suppression

Due to its short T1 and due to T2 elongation effects (Hardy et al. 1992; Stables et al. 1999), fat appears very bright on both T1-weighted (T1w) and T2-weighted (T2w) TSE imaging. The bright signal of fat can obscure pathology and hamper delineation of tumours that are bordering or invading fatty tissue. Examples are breast tumours, head and neck tumours, or mediastinal lymph nodes in oesophageal or advanced lung cancer. Fortunately a number of methods exist to suppress the bright signal of fat to enhance the contrast.

STIR. Short tau inversion recovery (Fleckenstein et al. 1991) is a fat suppression technique that relies on the short T1 relaxation of fat. The sequence consists of an inversion recovery pulse, followed by a specific inversion time (TI) that corresponds to the time at which the longitudinal magnetization of fat crosses zero. At that time the 90° excitation pulse, which puts the (non-zero) longitudinal magnetization of all other tissues into the transverse plane, is applied, and the data is collected. The technique is insensitive to off resonance, but the non-selective inversion causes a drop in SNR as it also partially

saturates the longitudinal magnetization of other tissues (Fig. 1.8c). By changing the TI, other species such as cerebral spinal fluid (CSF) can also be nulled. This technique is utilized by the fluid-attenuated inversion recovery (FLAIR) sequence (De Coene et al. 1992; Hajnal et al. 1992).

SPIR. Spectral presaturation with inversion recovery (Oh et al. 1988). This technique differs from STIR in the sense that the inversion pulse is a spectrally selective pulse. As a result only fat signal is inverted. The benefit compared to STIR is the improved SNR due to the fact that the longitudinal magnetization of the other tissues is unaffected by the inversion. The spectral-selective inversion, however, makes SPIR sensitive to B0 inhomogeneities and may therefore be less effective in regions like the thorax.

SPAIR. Spectral adiabatic inversion recovery (King et al. 2004). This technique is very similar to SPIR, except that the inversion pulse is changed to an adiabatic pulse, which makes the sequence insensitive to B1 inhomogeneities. SPAIR preparation usually takes a little longer than SPIR, leading to increased total scan duration. Figure 1.9c provides an example of SPAIR fat suppression.

DIXON imaging. The DIXON method (Dixon 1984) takes advantage of the resonance frequency offset between water and fat. Due to the difference in precession frequency between water and fat, a phase difference is introduced, which is a function of TE. For a frequency offset of 220 Hz (the frequency offset at 1.5 T), water and fat will be out of phase at TE = 2.3 ms and in phase at TE = 4.5 ms. When water and fat are out of phase, their signal will cancel, and the resulting signal will thus be reduced in voxels that contain both water and fat. The DIXON technique takes advantage of this phenomenon by acquiring multiple images with different TE. By solving a set of linear equations, the amount of water and fat can be calculated, and separate water and fat images can be produced. This technique has the advantage of high SNR and reduced sensitivity to B0 inhomogeneities, although at large field offsets, water-fat swaps can occur in the reconstructed images. In many cases DIXON is the preferred fat suppression technique.

1.3.1.3 Applications

The use of T1 and T2 with or without fat saturation is heavily dependent on the anatomical site and the type of tumour. T1-weighted imaging is often performed in conjunction with contrast enhancement. For H&N T1 pre- and post-contrast with fat saturation is used for GTV delineation and to assess tumour invasion into fat. In the prostate T1 Dixon is used to identify abnormalities, such as haemorrhages due to biopsies or fiducial marker implantation, as these lesions may look similar to tumour foci on T2w scans (Philippens 2016). T2-weighted imaging with fat saturation is used in H&N for the identification of oedema, delineation of salivary glands, and detection of metastatic lymph nodes. For rectum cancer, the GTV as well as the mesorectum and bladder are delineated on T2w scans, while in the lung, T2w-fatsat can be used to identify metastatic mediastinal lymph nodes (Cobben et al. 2015). T2w-FLAIR imaging is used to visualise oedema in the brain.

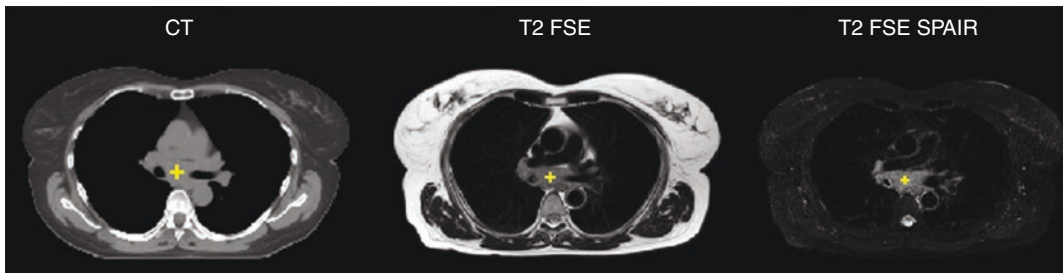

Fig. 1.9 Example of effective fat saturation in a stage III lung cancer patient. The T2-TSE with SPAIR fat saturation highlights a large positive mediastinal lymph node (N7). The T2 without fat saturation is acquired to define surrounding anatomy