A guide to magnetic resonance imaging in clinical practice

Introduction

Magnetic resonance imaging is an imaging modality that uses strong magnetic fields and radio waves to create diagnostic images. While a comprehensive knowledge of the underlying physics or detailed interpretation of these studies is beyond that required by junior doctors, this article outlines the indications, contraindications and safety requirements for this imaging modality and introduces the basics of magnetic resonance imaging physics and interpretation.

History

Magnetic resonance imaging has developed significantly over the last few decades and has had a long and interesting history. Nuclear magnetic resonance, the physical phenomenon in which nuclei in a magnetic field absorb and re-emit electromagnetic radiation, had been investigated by several Nobel Prize winning physicists including Isidor Isaac Rabi, who was awarded the Nobel Prize in Physics in 1944, and Felix Bloch and Edward Mills Purcell who shared the Prize in 1952. However, it was the crucial work of Paul Lauterbur and Sir Peter Mansfield, the latter a physicist at the University of Nottingham, England, that developed a way to generate the first magnetic resonance images using gradients and a mathematical technique that would allow scans to take minutes rather than hours, making this suitable for routine clinical use (Mansfield and Maudsley, 1977). Their work was recognized when they received the Nobel Prize in Medicine in 2003.

Dr D McKean *is Specialty Registrar in Radiology,* **Dr P Yoong** *is Clinical Fellow in Musculoskeletal Radiology and* **Dr CL McCarthy** *is Consultant Radiologist in the Department of Radiology, Nuffield Orthopaedic Centre, Oxford University Hospitals NHS Trust, Headington, Oxford*

Correspondence to: Dr P Yoong, Consultant Radiologist, Royal Berkshire Hospital, Reading RG1 5AN (philipyoong@gmail.com)

Indications: where magnetic resonance imaging is useful and not useful

Magnetic resonance imaging provides excellent soft tissue contrast and does not use ionizing radiation, unlike plain radiography (X-ray) and computed tomography. There are therefore a wide variety of indications in clinical practice. In many clinical scenarios it is the imaging modality of choice. However, there are more contraindications than for computed tomography scanning and scans take longer to perform and are very noisy.

It is important for junior doctors to understand the indications for magnetic resonance imaging compared to other cross-sectional imaging modalities.

Multidetector computed tomography gives more precise anatomical resolution of anatomy and multiphase acquisition is very useful in detection of acute bleeding. As such, multidetector computed tomography is the modality of choice for the assessment of acute trauma or haemorrhage. The superior spatial resolution of computed tomography also makes this the first-line test for delineation of the bony anatomy of complex fractures. Magnetic resonance imaging is also currently of limited utility in the investigation of lung diseases.

However, the improved tissue detail provided by magnetic resonance imaging makes this invaluable for the assessment of soft tissues and would be the modality of choice in many cases including ligament and tendon injury (*Figure 1*), pelvic pathology, spinal cord injury, and assessment of brain pathology.

Magnetic resonance imaging increasingly has a role in imaging acute pathology. For example the ability of magnetic resonance imaging to detect impaired diffusion may be crucial in the diagnosis and assessment of acute stroke, and the ability of magnetic resonance imaging to detect areas of acute inflammation make it a good alternative to computed tomography in pregnant women to avoid unnecessary radiation in patients for whom sonographic findings are non-diagnostic.

The development of new technologies such as positron emission tomography-magnetic resonance imaging integrated scanners and new molecular imaging techniques hold the promise of further advances in this field.

Physics

A magnetic resonance imaging scanner is a large static machine which uses a powerful magnetic field and radio waves to create images of the body. The time required for examination usually ranges from 10 to 90 minutes depending on the area being scanned and the number of sequences being

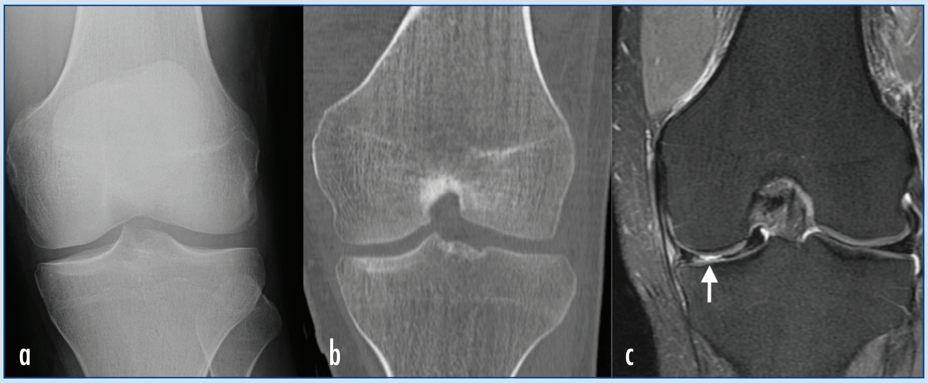


Figure 1. a. Frontal radiograph of the knee, (b) coronal computed tomography image and (c) coronal fat suppressed proton density magnetic resonance image. The superior soft tissue characterization of magnetic resonance imaging is demonstrated, enabling the musculature and intra-articular structures including a medial meniscal tear (arrow) to be seen.

obtained. The patient lies on a mechanical table which passes through the central bore of the magnetic resonance imaging machine. The bore comprises two sets of magnetic coils: the body coil and the gradient coil that are wrapped around the bore. These combine magnetism and radiofrequency pulsation to produce a pictorial representation of normal and abnormal soft tissue.

The strength of the magnetic field is measured in tesla (T) and most medical imaging systems operate at 1.5–3T. In comparison the typical strength of a refrigerator magnet is 0.005T or 5 millitesla (mT).

Magnetic resonance imaging is based on the ability of external magnetic fields to affect the nuclei of atoms. Hydrogen is particularly useful as it is abundant in soft tissue and, as a solitary proton, has a relatively high tendency to align with a magnetic field (magnetic moment).

Magnetic resonance images are obtained by placing the part under investigation into the strong magnetic field of the magnetic resonance scanner and then passing pulsed radiofrequency signals through this field. Between the pulses the hydrogen nuclei alternately relax and realign, emitting a characteristic radiowave of their own. Soft tissues vary in their water content, and hence concentrations of hydrogen nuclei, both according to their nature and whether or not inflammatory changes are present, and the resultant signals therefore vary. These signals can be detected and recorded, and computers are able to build a picture of the spatial relationships, density and tissue distribution of the hydrogen nuclei (Armstrong and Keevil, 1991).

Magnetic resonance appearances are described in terms of signal intensity, which refers to the strength of the radiowave that a tissue emits. The strength of this radiowave determines the degree of brightness of the imaged structures. A bright (whiter) area in an image is said to demonstrate high signal intensity, whereas a darker area is said to demonstrate low signal intensity.

There are two main types of magnetic resonance sequences, namely T1- and T2-weighted images. Generally, T1-weighted images provide good anatomical detail and T2-weighted images provide good contrast for evaluation of pathological processes. Different tissues display different signal intensities on T1- and T2-weighted images. These are summarized in *Figure 2* but the key to quickly differentiating between these sequences is to look for fluid (such as CSF), which should be dark on T1- and bright on T2-weighted images (*Figure 3*).

In order to increase the contrast between pathology and normal tissues contrast agents may be used, typically gadolinium. These agents may be given via an intravenous, oral or intra-articular route and have a high signal on T1-weighted images. Contrast agents are frequently used in brain imaging.

Other commonly used magnetic resonance sequences include:

- Proton density weighting, resulting in an image that could be described as being halfway between a T1- and T2-weighted image. Whereas in a T2-weighted image fluid appears bright, in a proton density-weighted image fluid appears grey, which often increases the visibility of subtle pathology. It is often combined with techniques that reduce the signal from fat, referred to as fat suppressed proton density weighted imaging.
- Short tau inversion recovery (STIR) where the signal from fat is suppressed, so fat appears dark. This makes oedema and pathology much more conspicuous.
- Fluid-attenuated inversion recovery (FLAIR) where the signal from fluid is suppressed, so fluid appears dark.
- Diffusion weighted imaging, where the amount of diffusion of water molecules is measured, producing a representative image. Reduced diffusion is seen in acute stroke and malignancies, and diffusion weighted imaging is therefore often used in brain and cancer imaging.

Basic interpretation of images

Reporting magnetic resonance imaging scans is beyond the level expected of junior doctors, but an understanding of the basic principles of image interpretation is extremely useful. As a guide, junior doctors should be able to follow image-based discussions at their multidisciplinary team meetings as this will significantly augment their understanding of their specialty. The following is a brief introduction to image interpretation.

As described above, there are a large number of magnetic resonance imaging sequences, which can be acquired in any plane. However, as acquiring more sequences takes time to perform and also takes longer for a radiologist to interpret, a radiology department will have standard sequences for each body part, depending on the indication for the scan. These sequences will be a trade-off between providing sufficient information for the radiologist to arrive at a diagnosis and the time taken to perform the scan. For instance, in the authors' institution, there are four sequences in a standard magnetic resonance imaging scan of the lumbar spine: T1 sagittal, T2 sagittal, T1 axial and T2 axial.

As with all cross-sectional imaging, accurate interpretation depends upon good anatomical knowledge and an awareness of differences between axial, coronal and sagittal planes. An axial plane represents 'slices'

Figure 2. A simplified diagram illustrating the T1 and T2 characteristics of various substances. The most important point is that fluid and therefore most pathology is dark on T1 and bright on T2-weighted images.

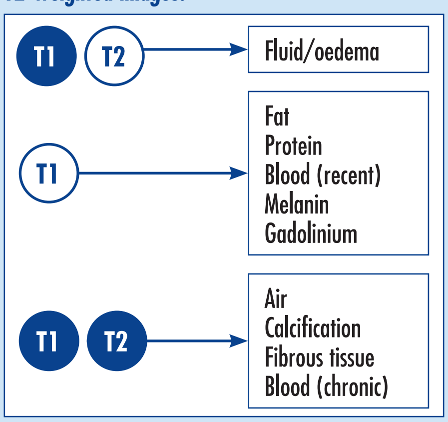


Figure 3. a. Sagittal T2 and (b) T1-weighted images of the lumbar spine. Note that the normal CSF in the spinal canal and urine in the bladder (asterisk) is bright on T2. Note that fat returns high signal on both T1- and T2-weighted images.

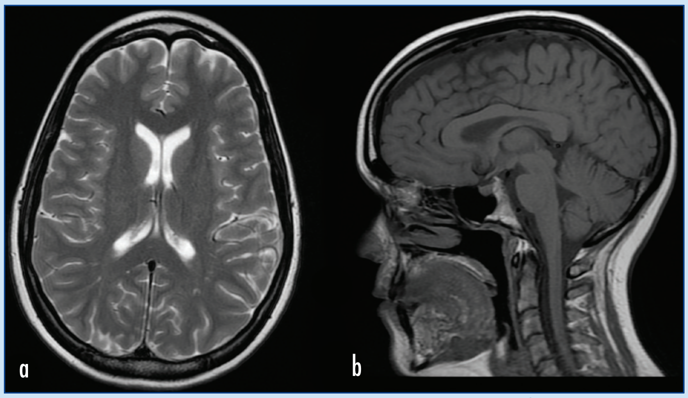


Figure 4. a. Axial T2 and (b) sagittal T1-weighted images of the adult brain. Note that the normal CSF fluid in the ventricles is bright on T2. The gray matter is darker than white matter on T1.

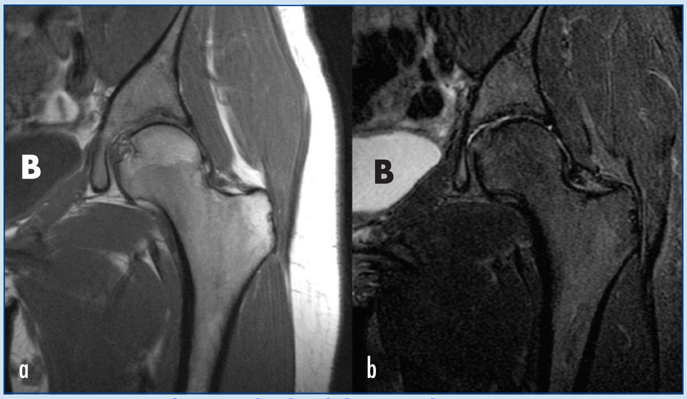
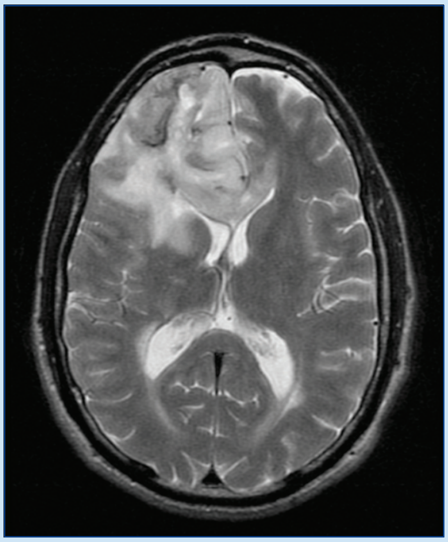


Figure 5. a. Coronal T1-weighted and (b) STIR (short tau inversion recovery) images of a normal left hip. Note that the urine in the bladder (B) is dark on T1 and bright on STIR. Also note that the subcutaneous fat is dark on STIR.

through the body, a coronal plane divides the anterior and posterior parts of the body, and a sagittal plane the left and right sides of the body. On an axial image, the left side of the patient will be on the right side of the image: it is useful to imagine that the patient's feet are closest to you, pointing upwards.

Figure 6. Axial T2-weighted image of the brain, The oligodendroglioma in the right frontal lobe results in high T2 signal and mass effect.



A useful way to orientate oneself regarding the types of sequence used in any particular image is to look at the signal of structures that contain fluid such as the ventricles of the brain, the CSF in the spinal canal, the gall bladder and the urinary bladder. If this is bright, then the images are T2 weighted and if this is dark then the images are probably T1 weighted (*Figure 4*). In the normal brain, the gray matter is darker than the white matter on a T1-weighted image. In many magnetic resonance imaging sequences, the signal from fatty tissue will have been suppressed in order to highlight pathology from non-fatty surrounding structures. Look at the subcutaneous fat or normal bone marrow: if it seems dark then the image is likely to have been obtained using a fat suppressing sequence such as short tau inversion recovery (STIR) or T2 fat saturation (*Figure 5*). If contrast medium has been administered, there will typically be high signal in structures that contain blood, such as vascular structures.

Once the location, plane and sequence of the images have been established, consider whether there might be any pathology on them. Think about the clinical question that you were trying to ask and focus on that area. A useful tip is to look for areas that are bright on T2-weighted images. Most pathology involves oedema and inflammation, which are bright on T2 and dark on T1 (*Figures 6–9*). T1-weighted images are typically better for providing contrast between different types of soft tissues and are therefore useful for demonstrating anatomy, both normal and abnormal. As mentioned above, typical fluid is dark on T1 images. In contrast, the following five materials are bright on T1-weighted images: fat, protein, subacute blood, mela-

Figure 7. a. Sagittal and (b) axial T2-weighted images of the lumbar spine showing a left paracentral L5/S1 disc herniation (arrows), compressing the left S1 nerve root.

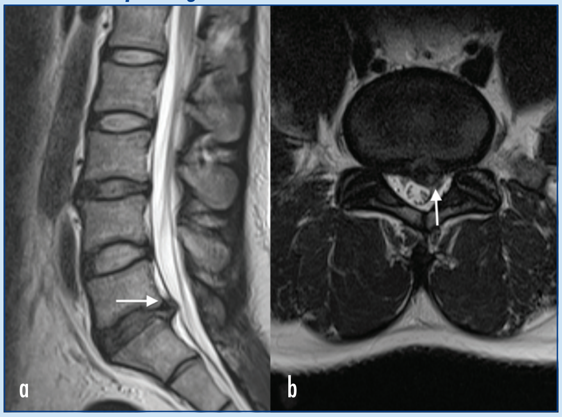
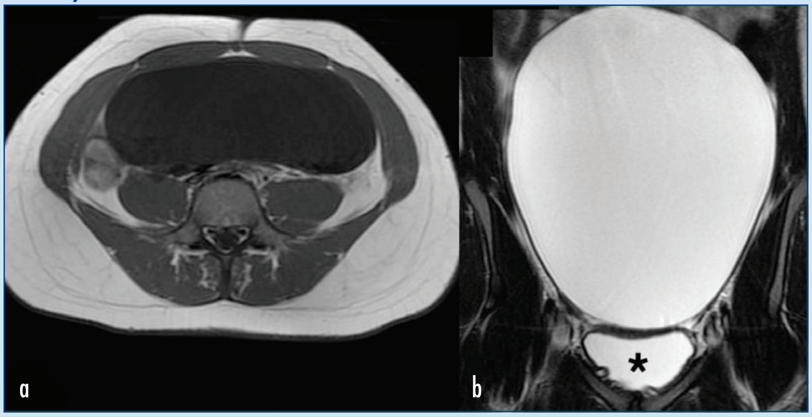


Figure 8. a. Axial T1-weighted and (b) coronal T2-weighted images of the abdomen. A large ovarian cyst (dark on T1 and bright on T2) is seen. The normal bladder (asterisk) is seen inferiorly.



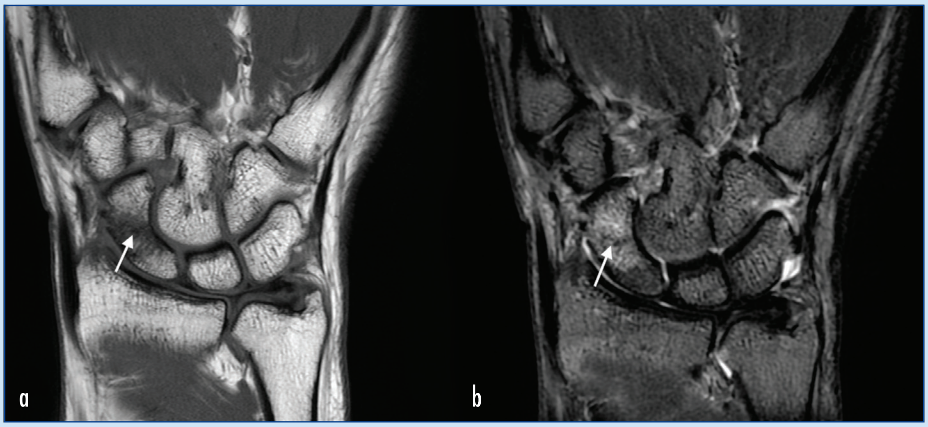


Figure 9. a. Coronal T1-weighted and (b) STIR (short tau inversion recovery) images of the wrist. The acute scaphoid fracture (arrows) was not seen on a radiograph from the previous day. Adjacent bone marrow oedema returns low T1 and high STIR signal.

nin (seen in melanoma) and gadolinium contrast media (*Figure 10*).

For example, imagine a hypothetical case of a disorientated patient with a history of metastatic melanoma who has a magnetic resonance imaging scan of the brain. The T2 sequence can be recognized by looking at the ventricular system of the brain, which has high signal CSF within it. If the cause is melanoma metastases to the brain, there will probably be foci of high T1 signal (melanin) surrounded by low T1, high T2 signal (oedema) with asymmetry of the brain parenchyma.

To summarize, consider which part of the body has been imaged, the plane of the image, the sequence, whether contrast has been administered or not, and whether there is any abnormality. This will help you to interpret magnetic resonance images.

Safety

While magnetic resonance imaging is an extremely safe procedure there are several safety issues related to exposure to a strong magnetic field.

Changes in blood pressure and heart rate have been observed in human subjects. However, these have been within the range of normal physiology for exposure to magnetic fields up to 8T. Exposure to radiofrequency radiation also causes increased oscillation of molecules and heating. However, the degree of heating generated during a medical magnetic resonance imaging scan can be well tolerated by an individual with normal thermoregulatory function (Shellock et al, 1994).

A much more significant risk comes from the projectile effect of ferromagnetic material in a strong magnetic field. Patient fatalities have been reported and further 'near misses' have occurred with oxygen facilities being inadvertently allowed into the magnetic resonance room. Extreme caution is therefore necessary and strict screening protocols should be maintained to prevent ferromagnetic items entering controlled areas. Particular care is needed when equipment for patient assessment is brought into the magnetic resonance environment, especially in an emergency setting and, owing to the potential hazards of the static magnetic field, resuscitation of patients should ideally take place outside the controlled area.

The magnetic field can also affect implantable medical devices in any exposed individuals. Any ferromagnetic components within implantable medical devices may experience both an attractive force and a torque force. These effects have the potential to cause both tissue damage and damage to the implanted device.

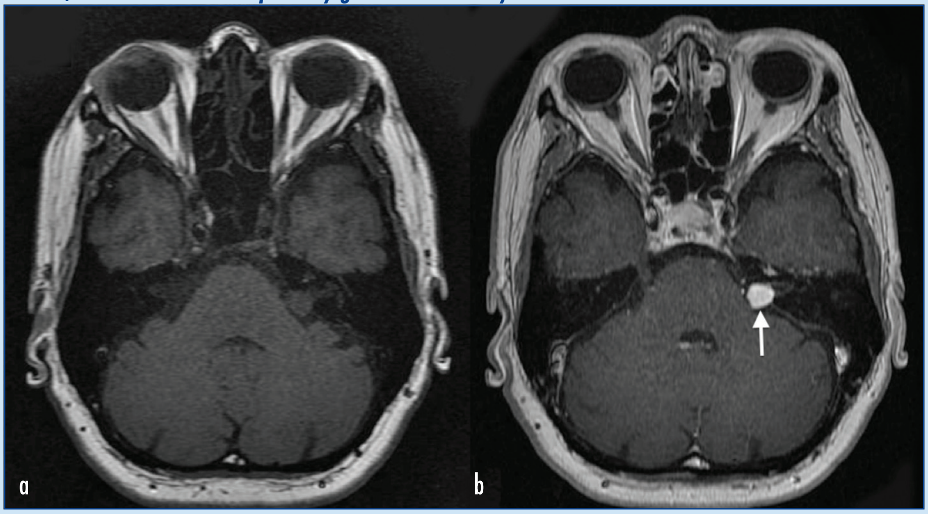
Examples of implanted devices include stents, clips, prostheses, pacemakers and neurostimulators. There is considerable variation in the range of implantable devices and it is therefore essential to ensure the relevant devices are magnetic resonance compatible before any investigation. However, cardiac pacemakers, cardioverter defibrillators, cochlear implants and neurostimulators should be considered as absolute contraindications to magnetic resonance imaging. Intraocular foreign bodies are also an absolute contraindication and a radiograph of the orbits should be performed if there is a suspicion of this.

If the use of contrast agents is being considered, it is important to know that these are relatively safe compared to the iodinated contrast media used in computed tomography scanning.

Gadolinium-based contrast agents are usually well tolerated with a reported incidence of adverse reactions of 0.48% (Li et al, 2006). The majority of adverse reactions to gadolinium-based contrast media are mild and transient (96%), with the most frequently reported reactions being nausea and vomiting or an urticarial rash. Those with pre-existing allergy to other contrast agents are at increased risk and these patients should be identified before any contrast administration.

However, renal function should be checked before any contrast-enhanced magnetic resonance imaging scan to reduce

Figure 10. Axial T1-weighted (a) pre- and (b) post-contrast images of the brain. The left acoustic schwannoma (arrows) is more clearly seen after contrast administration. Note that in b the nasal mucosa, cavernous sinus and pituitary gland also normally enhance with contrast.



the risk of nephrogenic systemic fibrosis, a very rare but serious complication that may occur in patients with renal impairment (Cowper et al, 2000). Patients typically develop large areas of hardened skin with fibrotic nodules and plaques. This may cause joint contractures causing limitation in motion. In its most severe form, nephrogenic systemic fibrosis may cause severe systemic fibrosis affecting internal organs including the liver, lungs, muscles, heart and nerves. Nephrogenic systemic fibrosis is usually a chronic, progressive condition without effective treatment. Current recommendations for prevention are limiting the use of gadolinium-based contrast agents and optimizing renal function in those with impaired renal function.

Given the number of safety issues it is important that patients are screened appropriately. A sample magnetic resonance imaging safety checklist is given in *Table 1*.

Table 1. Sample magnetic resonance imaging safety checklist

What is your weight?
Do you have a cardiac pacemaker or defibrillator?
Have you ever had a cardiac pacemaker or defibrillator?
Have you ever had heart surgery?
Do you have any type of electronic, mechanical or magnetic implant?
Have you ever had any type of electronic, mechanical or magnetic implant?
Have you ever had surgery to your head, brain, eyes or ears?
Have you ever had any metal fragments in your eyes?
Have you ever had any metal fragments in any other part of your body?
Have you ever had any operations involving the use of metal implants, plates or clips?
Have you had any surgery in any part of your body in the past 6 weeks?
Do you have any wound dressings?
Are you wearing any medication patches?
Have you been told your kidneys are not working properly?
For women:
Could you be pregnant?
Are you breast-feeding?

Patient experience

Patients should be consented for magnetic resonance imaging scans and made aware of what to expect during the procedure.

A patient will have to lie still and flat within an enclosed space for a period of time in a noisy environment, typically between 10 and 90 minutes, depending on the body part or parts to be imaged.

Claustrophobia, confusion, anxiety, pain and shortness of breath are therefore patient-related factors that may limit tolerance of a magnetic resonance imaging scan.

An increasingly common problem limiting access to magnetic resonance imaging is patient girth. Obese patients may not be able to pass through the bore of the magnetic resonance imaging scanner. There are also limitations on the weight that the mechanical table may support and these should be assessed before requesting an examination.

The magnetic resonance imaging machine is operated by a radiographer in a room adjacent to the scanner and its magnetic field. However, patients are able to communicate with the radiographer through an intercom and will be monitored by the supervising radiographers throughout the scan. Patients should also be counselled that it is essential that they remain as still as possible during their procedure as movement-related artefact may render images non-diagnostic.

Patients who suffer from claustrophobia should be counselled before a scan. If is this is not acceptable to them, an open magnetic resonance imaging scan should be considered, if available. Open magnetic resonance imaging use permanent magnets but have lower field strength with associated sacrifices in image quality. Claustrophobia, anxiety, confusion and pain can be addressed with appropriate counselling, analgesia and sedation before a scan.

Acoustic noise, caused by the gradient coils switching on and off during the scan, can reach uncomfortable levels. In general, the higher the field strength, the higher the acoustic noise level (Price et al, 2001). The simplest means of minimizing the potential of magnetic resonance-related acoustic noise problems is the use of ear defenders, ear plugs or other means of hearing protection.

Conclusions

Magnetic resonance imaging is ubiquitous in hospital medicine and has revolutionized patient care. Although a detailed knowledge of magnetic resonance physics and competence at image interpretation is the remit of the radiologist, junior doctors should be aware of the fundamentals of magnetic resonance imaging as part of a holistic approach to managing their patients, as well as fostering good relationships with their radiology department. **BJHM**

Conflict of interest: none.

Armstrong P, Keevil SF (1991) Magnetic resonance imaging: Basic principles of image production. *BMJ* **303**(6793): 35–40

Cowper SE, Robin HS, Steinberg SM, Su LD, Gupta S, LeBoit PE (2000) Scleromyxoedema-like cutaneous diseases in renal-dialysis patients. *Lancet* **356**(9234): 1000–1

Li A, Wong CS, Wong MK, Lee CM, Au Yeung MC (2006) Acute adverse reactions to magnetic resonance contrast media–gadolinium chelates. *Br J Radiol* **79**(941): 368–71

Mansfield P, Maudsley AA (1977) Medical imaging by NMR. *Br J Radiol* **50**(591): 188–94

Price DL, De Wilde JP, Papadaki AM, Curran JS, Kitney RI (2001) Investigation of acoustic noise on 15 MRI scanners from 0.2 T to 3 T. *J Magn Reson Imaging* **13**(2): 288–93

Shellock FG, Schaefer DJ, Kanal E (1994) Physiologic responses to an MR imaging procedure performed at a specific absorption rate of 6.0 W/kg. *Radiology* **192**(3): 865–8

KEY POINTS

- Magnetic resonance imaging is excellent for differentiating soft tissues whereas computed tomography and X-ray are not.
- A patient needs to lie flat and still for some time in a noisy environment. Consider and address factors that may affect this such as anxiety, confusion, pain, shortness of breath and claustrophobia.
- Absolute contraindications are intraocular foreign bodies, pacemakers, internal cardiac defibrillators and cochlear implants. Ask about these before ordering a scan.
- T2-weighted images can be differentiated from T1-weighted by looking at areas that normally contain fluid, such as the bladder. Fluid is bright on T2-weighted images. As most pathology involves oedema, look for high T2 signal to indicate pathology.
- Fat, protein, melanin, subacute blood and contrast are bright on T1.