MINI-SYMPOSIUM: RADIOLOGY FOR THE FRCS (Orth)

(ii) Basic science: magnetic resonance imaging

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**Summary**

Plain film radiography is the mainstay of orthopaedic investigation. Magnetic resonance imaging (MRI) is however now being utilised more frequently and reveals pathology that may have been overlooked with the plain film.

This paper describes the basic science of MRI. It also describes the most frequently used sequences in orthopaedic MRI, MRI safety, and types of scanner, artefacts and the use of gadolinium.

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**Introduction**

Plain film radiology has been the mainstay of orthopaedic investigation since the discovery of X-rays but recently Magnetic Resonance Imaging (MRI) has become more widely available, and is now an indispensable tool in the investigation of musculoskeletal pathology.

A thorough understanding of MRI physics is not necessary but a background knowledge is useful in order to appreciate why certain sequences are used and to assist in image interpretation. The main sequences used in daily practice are T1 and T2 sequences with STIR (FAT saturation), PD (proton density) and T1 post gadolinium sequences used as ancillary methods depending on the clinical question, with imaging performed in transverse, sagittal and coronal planes according to the anatomical site of interest.

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**The basic physics of MRI**

MRI is based on the process of Nuclear Magnetic Resonance, a process involving the absorption and emission of energy by atomic nuclei in the presence of an externally applied magnetic field. Hydrogen proton nuclei are used to generate the image, as they are by far the most abundant nuclei in the body with the greatest concentration in water and lipid molecules. The patient is placed in the MRI scanner and energy is applied in the form of radiofrequency pulses which are designed to match the resonant frequency of hydrogen atoms, which absorb these energy pulses. After each radiofrequency pulse has been applied, the hydrogen atoms re-emit this energy as a magnetic resonance signal which induces a small voltage in a receiver coil placed next to the patient.

The hydrogen atoms return to a relaxed state by two mechanisms known as T1 and T2 relaxation which are dependent on molecule size and binding to larger macromolecules. All tissues e.g bone,
marrow, fluid/oedema, tumours, muscle, cartilage, ligaments and tendons have different T1 and T2 relaxation times. This principle is used to detect the emitted energy from the hydrogen atoms after the radiofrequency pulse has been applied by varying the time to detect the signal (TE—time to echo) and the time to apply the next radio-frequency pulse (TR—time to repetition). Liquids have long T1 and T2 values whilst fat has short T1 and T2 values, thus varying the TE and TR can weight the sequences as either T1 or T2. For example, increasing the time to echo and time for pulse repetition will produce a T2 weighting which is sensitive for fluid which accumulates in pathological conditions such as oedema, inflammation infection and in tumours. On T1 weighted sequences fat returns a high signal but the converse is true for fluid. Therefore a region of bone bruising would appear as a region of low signal next to the high signal fatty marrow on T1 sequences but would appear bright on a T2 sequence.

**MRI safety**

Any ferrous containing object is potentially dangerous within the MRI scanning room unless secure. Hearing aids, jewellery, watches, glasses, prostheses, credit cards and any type of implant should be removed before entering the scanner as they can potentially become a dangerous projectile.

Orthopaedic implants including prosthetic joints, pins, rods, screws, nails, clips, plates or K wires are not contraindicated although they significantly degrade image quality with less artefact produced by titanium devices.

Objects such as oxygen cylinders or trolleys must not be taken into the scanning suite unless they are MRI compatible.

The following objects are contraindicated:

- Cardiac pacemakers
- Implanted defibrillators, neurostimulators and insulin pumps
- Swan Ganz catheters
- Orbital metallic foreign bodies (if suspected then X-ray the orbits)
- Any intravascular coils, filters or stents (some may be compatible)
- Cochlear implants (possible compatibility)
- Aneurysm clips (possible compatibility)

The following are MRI compatible:

- Surgical clips 6 weeks post procedure
- Superficial staples
- Vascular lines
- Intrauterine contraceptive devices
- HALO spinal vest
- Penile prosthesis (compatibility must be checked)
- Heart valves (compatibility must be checked)

Patients may not tolerate the confined space of the MRI scanner and therefore prior to requesting an MRI it is advisable to ask the patient if they suffer from claustrophobia. Sedation can be administered if there are qualified staff available to supervise but in cases of severe claustrophobia where investigation is paramount and in infants, general anaesthesia can be given provided there is compatible anaesthetic equipment.

It is imperative that conscious patients remain still during the examination as motion artefact dramatically degrades image quality.

**Types of scanner**

The strength of a magnet correlates with image quality although very high field strengths may paradoxically lead to increased artefact. The optimal strength for orthopaedic work is regarded as 1.5 T (Tesla); however 0.5 T low field magnets can be used but image quality may be compromised. Low field strength magnets degrade image quality and lengthen examination time thus further degrading the image by movement artefact.

Patients who are intolerant of standard tunnel MRI scanners due to claustrophobia may tolerate an open magnet, which is also suitable for very large patients. These magnets usually generally operate at lower field strengths (Fig. 1).

Short bore magnets have also been developed that combine the high field strength and anatomical accuracy of a tunnel magnet with the comfort of an open magnet (Fig. 2).

Recently the advent of standing or sitting MRI scanners are available which allow imaging, particularly of spines and weight bearing joints to be performed in more anatomical positions (Fig. 3).

**MRI sequences**

(1) T1—short TR (TR < 1000 ms), short TE (TE < 60 ms)

This is a short sequence, which can be rapidly acquired. Anatomical detail and spatial resolution are excellent. Fat, sub acute haemorrhage and
proteinaceous fluid are bright. Fluid is however dark on T1. T1 is good for looking for meniscal pathology and marrow. It is however less good at detecting oedema when either T2 or STIR would be optimal (Fig. 4).

(2) T2—long TR (TR > 1000 ms), long TE (TE > 60 ms)

This is a long sequence. Fluid is bright and because most pathological processes involve oedema, it highlights the area of abnormality (Fig. 5).

(3) Proton density (PD)—long TR(TR > 1000 ms), short TE (TE < 60 ms)

This sequence is a mix of T1 and T2. The contrast is a function of the number of protons in the tissue.
and is intermediate between T1 and T2. PD sequences are most commonly used in the assessment of the menisci as part of routine knee protocols (Fig. 6).

(4) STIR/SPIR—Fat suppressed inversion recovery techniques (TR > 1000 ms), (TE TE > 60 ms), (TI time to inversion) = 120–150 ms)

The contrast between fat and water is low on T2 sequences as both return a high signal, and therefore fluid can be missed. This technique decreases the signal intensity from fat and strikingly enhances the signal from fluid and oedema. It is therefore a very sensitive tool for detecting soft tissue and marrow pathology. Some centres use a similar technique of fat suppressed T2 sequences. Fat suppression may be used to confirm the fatty nature of a lipoma (Fig. 7).

(5) T2*—gradient echo T2 (TR variable, TE < 60 ms, flip angle = 10–80°)

This is an accelerated T2 sequence. Fluid appears bright as with other T2 sequences. It is particularly good at imaging ligaments and articular cartilage, particularly fibrocartilage such as the menisci and labrum of the hip and glenoid. The images can be acquired in extremely thin 3D volumes making it very useful in assessing small structures such as the ligaments of the wrist and reconstruction is possible in various planes.

The sequence is however degraded significantly if adjacent tissues have widely differing magnetic properties such as metal and soft tissue resulting in susceptibility artefact. This phenomenon may however be put to use when looking for subtle haemorrhage which results in a “blooming artefact” due to breakdown products of haemoglobin.

(6) Fast spin (Turbo) echo

This is an accelerated method of acquiring T2 and PD images, as the normal acquisition time can be lengthy. In general accelerated, fast or ‘turbo’ techniques are utilised routinely for acquiring all sequences.

Both T2 and PD sequences can be acquired at the same time, reducing imaging time and therefore decreasing motion artefact. However, on fast spin echo T2 sequences fat remains quite bright and lesions within bone marrow which would also be bright on T2, may be missed. This can be overcome by using fat saturated STIR/SPIR sequences (see section 4, above). In addition, on fast spin echo PD image degradation may result in meniscal pathology not being seen. The degradation in image quality is miniscule but this is offset by the dramatically reduced scanning time compared with standard T2 acquisitions.

Metal prostheses obscure anatomy due to susceptibility artefact. Fast spin echo techniques however reduce the artefact and should be employed if there has been previous instrumentation. All sequences however will show artefact to a
lesser or greater extent due to metallic foreign structures (Fig. 8).

Gadolinium is a paramagnetic contrast agent that causes tissue enhancement in vascular structures when administered intravenously. Enhancement is best evaluated on T1 sequences and fat saturation may also be used to optimise the enhancement especially when the abnormality is situated within fatty tissue which would also be bright on T1.

It can help discriminate between a cystic or solid mass, viable from necrotic tissue, infection from inflammatory tissue and a recurrent intervertebral disc from postoperative scar tissue.

Intra-articular dilute gadolinium is also used in detecting labral tears, meniscal tears in

Figure 7 T1 axial image of the upper arm showing a high signal intramuscular soft tissue mass. The signal is suppressed on the STIR sequence and is diagnostic of a lipoma.

Figure 8 Previous removal of Harrington rods. T1 Sagittal thoracic spine image. The artefact is from tiny remnant metal fragments causing severe image degradation.

Figure 9 Wrist Arthrogram—T1 with fat suppression showing contrast in the mid carpal joint, proximal carpal joint and radiocarpal joint.
postoperative knees, ligamentous injuries, and osteochondral defects (Fig. 9).

**Sequences specific for particular tissues (Table 1)**

**Collagen**: Some tissues such as ligaments, tendons and fibrocartilage do not contain free hydrogen atoms to contribute a signal and are therefore dark on T1 and T2 sequences.

Structures containing collagen may demonstrate artefactual high signal due to the magic angle effect which occurs when the collagen bundles are orientated at 55° to the magnetic field. It is most prominent in T1, PD and T2*(short TE sequences), but disappears on T2W and STIR (long TE sequences) and can be a problem in particular when assessing the rotator cuff tendons.

**Marrow**: Haemopoietic marrow seen in the paediatric population is brighter than muscle but darker than fat on T1 sequences and therefore must not be interpreted as pathology. STIR and fat suppressed T2 are the optimal sequences for looking for marrow pathology and bone bruising in trauma whilst T1 sequences are used to look for fracture lines which can be missed on T2 owing to the surrounding oedema.

**Muscle**: T1 and STIR are used to depict muscle architecture and localise oedema indicating the site of pathology.

**Cartilage**: STIR or fat saturated fast spin echo T2 are used to assess cartilage. Many MRI scanners have a specific cartilage sensitive sequence which may also be used.

Fibrocartilage and hyaline cartilage return a dark and intermediate on all sequences respectively. Menisci are optimally visualised with T1, PD and T2*.

The glenoid and acetabular labrum are best seen with T1W post intra-articular gadolinium and T2*.

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<thead>
<tr>
<th>Table 1</th>
<th>Clinical question</th>
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<tr>
<td>Bone</td>
<td>Fracture</td>
<td>T1, STIR</td>
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<tr>
<td>Marrow</td>
<td>Malignancy/mets</td>
<td>T1, T2*</td>
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<tr>
<td>Muscle</td>
<td>Injury</td>
<td>T1, STIR</td>
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<tr>
<td>Soft tissue</td>
<td>Malignancy</td>
<td>T1, STIR if mass and high signal on STIR then Gadolinium enhancement</td>
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<tr>
<td>Tendons/ligaments</td>
<td>Rupture/strain</td>
<td>T1,T2*,STIR</td>
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<td>Menisci</td>
<td>Tear</td>
<td>T1, PD, T2*</td>
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<td>Labrum</td>
<td>Tear</td>
<td>Arthrogram T1, T2*</td>
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<tr>
<td>Synovium</td>
<td>Inflammation</td>
<td>Pre and post gadolinium T1</td>
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<th>Table 2</th>
<th>Body area</th>
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<tr>
<td>Knee</td>
<td>SE PD/T2</td>
<td>Sagittal</td>
<td>Coronal</td>
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<tr>
<td></td>
<td>SE T1</td>
<td>Coronal</td>
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<td></td>
<td>STIR</td>
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<tr>
<td></td>
<td>PD SPIR</td>
<td>Axial</td>
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<tr>
<td>Shoulder</td>
<td>T2</td>
<td>Axial</td>
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<td></td>
<td>SE T1</td>
<td>Coronal oblique</td>
<td></td>
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<tr>
<td></td>
<td>T2 SPIR</td>
<td>Coronal oblique</td>
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<tr>
<td></td>
<td>SE T1</td>
<td>Sagital oblique</td>
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<td>T2 SPIR</td>
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<td></td>
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<td></td>
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<td>T2 SPIR</td>
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**Synovium**: The synovium is difficult to visualise unless it is abnormal where it enhances post contrast administration but is indistinguishable from fluid on T2 and STIR sequences.

**Sequence and planes**

The following sequences and planes are the most frequently used; the site of anatomy and the clinical question determine what protocol is used (Table 2).
Axial, sagittal and coronal imaging are the mainstay, but oblique imaging particularly of the shoulder tendons is useful.

**How do you determine the sequence from the film?**

When confronted with a series of MRI images, the first thing to do is identify known areas of fluid, for example CSF, hydrated intervertebral discs, the urinary bladder and renal pelvis. If these areas return a high signal, then the image is T2 weighted. If the fluid is bright and the fat is dark then it is most likely a fat suppressed T2 image such as a STIR.

If fat is bright and the fluid is dark then it is likely to be a T1 weighted image. PD may be difficult to determine but has intermediate signal fat and soft tissue. The contrast in a PD is not as great.

Contrast enhanced scans are usually labelled and are usually T1 sequences with or without fat suppression. Fat in these cases will then be dark and the images are usually compared with the T1 images pre-contrast to ascertain the degree, if any of enhancement.

**Conclusion**

Although there have been numerous advances in the number of imaging sequences in MRI, the basic principles still apply. The sequences used are tailored to yield the most amount of information in the shortest time. It is however important that there is good interaction between the orthopaedic surgeon and radiologist so that a succinct answer to the clinical question is achieved by optimising the sequences and planes used. Although the radiologist’s role is to protocol and report the MRI images, with some basic background knowledge the orthopaedic surgeon should be able to appreciate the sequences used and identify pathology on MRI studies, which will benefit them in patient assessment and management.