MRI of the whole body

AN ILLUSTRATED GUIDE TO COMMON PATHOLOGIES

Edited by
Kshitij Mankad
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HODDER ARNOLD

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RSM
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Preface

MRI of the Whole Body: An Illustrated Guide to Common Pathologies was envisioned as a book to help and guide junior radiologists contriving to learn the basics of clinically applied magnetic resonance imaging. As trainees, the authors often felt the need for a manual that could provide an overview of the modality as applicable to common diseases. Apprentice-modelled MRI teaching continues to be, by and large, *ad hoc*, and voluminous textbooks rarely leave their respective shelves. It is hoped that this illustrated guide will fill the gap and provide the first steps in dispelling the myths of MRI that often cloud the impressionable minds of trainees, residents, fellows, radiographers and general radiologists.

The guide covers all subspecialties and is written in a simplified manner with limited but vital textual matter and greater emphasis on key sequences and protocols, with hints and tips to typical imaging features of common pathologies and their close differential diagnoses.

We are extremely grateful to all our contributing authors and editors and the Royal Society of Medicine Press for having accepted the initial manuscript and for their patience and support throughout this project.

K Mankad
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Dedication

To our families with love and gratitude for their unflinching support.

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UNIT I

MRI of the Musculoskeletal System

Amit Lakkaraju, Ram KP Vijay

1 MUSCULOSKELETAL IMAGING

MRI PROTOCOLS

Introduction

MRI protocols for imaging in musculoskeletal conditions vary depending on the part to be imaged, the specific tissues that need to be imaged, and the type of pathology. There is a need to standardize protocols to provide uniformity of imaging and to replicate previous scans.

Scanning of the extremities requires dedicated coils to allow better resolution compared with body coils. The use of phased array coils has become standard, since they are able to obtain maximum signal from each segment of tissue covered.

The sequences commonly used in musculoskeletal imaging are listed in Table 1.1.

Fat-suppression techniques

Fat suppression is a commonly used technique in musculoskeletal MRI. Unsuppressed fat is relatively high signal on both T1- and T2-weighted imaging. The technique is used to delineate oedema from the fat signal.

Two main methods are used to suppress fat: frequency-selective fat saturation and STIR imaging.

Frequency-selective fat saturation

This uses a pulse to cancel out the signal from fat without affecting the signal from water.

In T1-weighted imaging, this technique is used to confirm the nature of fatty tissues and also when gadolinium enhancement is employed.

T2-weighted fast spin echo (FSE) imaging is combined with frequency-selective fat suppression to visualize soft tissue and bone marrow oedema. A major problem with this technique is that it is susceptible to inhomogeneities in the magnetic field and to magnetic susceptibility artefact.

Short-tau inversion recovery (STIR) imaging

This uses an inversion recovery technique to suppress fat. There is an initial inversion pulse at 180° to the longitudinal axis, followed by an excitation pulse at 90° when the recovery of the fat signal reaches zero, thereby removing the signal.

STIR is used when imaging larger fields of view, since the sequence is less susceptible to field inhomogeneities.

STIR is not used with gadolinium enhancement, since the relaxation properties of gadolinium and fat are very similar and so the enhancement would be suppressed along with fat.

Gadolinium enhancement

Gadolinium (Gd) is a rare earth element, whose ion Gd^{3+} contains seven unpaired electrons. The contrast agent Gd-DTPA is a paramagnetic stable compound that demonstrates high signal on T1-weighted imaging. It can be administered by either intravenous or intra-articular injection.

Table 1.1 Sequences used in musculoskeletal MRI[a]

Sequence	TR (ms)	TE (ms)	TI (ms)/flip angle	Strengths/weaknesses
T1-weighted	<1000	≤30		Good anatomic detail and meniscal pathology
Proton density (PD)-weighted	>1000	30–60		Marrow pathology and anatomic detail
T2-weighted	>2000	≥60		Good for oedema, but there is a potential blurring artefact Tissue oedema needs fat saturation for better delineation
T2-weighted gradient echo (GRE)	Variable	≤ 30	5–20°	Good for imaging tendons and ligaments, but poor for marrow pathology and there is a susceptibility artefact
Short-tau inversion recovery (STIR)	≥2000	≥60	120–150 ms with 180°→90°	Marrow and tissue pathology, but not good for using with gadolinium
T1-weighted fat saturation (FS) with Gd				Good for removing the signal from fat so that gadolinium enhancement is seen better

[a]Adapted from Kaplan P, Dussault R, Helms CA, Anderson MW. *Musculoskeletal MRI*, 1st edn. Philadelphia: WB Saunders, 2001.

Contrast enhancement is best seen on T1-weighted fat saturation sequences, where there is enhancement of only those tissues that take up the Gd.

Gd enhancement is used in very specific cases in musculoskeletal MRI, principally the following:

- **Cystic versus solid lesions:** a true cyst will demonstrate only wall enhancement, while a solid lesion will show diffuse enhancement.
- **Tumour:** Gd is used to differentiate solid from cystic tumours and may help in targeting biopsies.
- **Infection:** Gd enhancement is useful in differentiating solid areas from phlegmon and abscess. Abscess shows a thick enhancing wall. Sinus tracts can be better detected by this technique. However, Gd is of no use for differentiating osteomyelitis from marrow oedema, both of which present as marrow enhancement.
- **Spine:** a recurrent disc does not enhance following Gd, while postoperative fibrosis does. This is a useful discriminator in postoperative spinal imaging, although the management of these conditions is similar.
- **MR arthography:** this technique is used to locate pathology within the shoulder and the hip. It can be used to look at labral tears. A 1% Gd solution is injected into the joint (concentrated solutions result in loss of signal from the fluid and render images non-diagnostic). T1-weighted imaging with fat saturation is used to distinguish Gd from fat, along with a T2-weighted sequence in at least one plane to detect oedema or cysts.

TIPS ON INTERPRETING MUSCULOSKELETAL MRI

Interpretation of musculoskeletal MRI needs a combination of skills.

First and foremost is the clinical history, which points fairly accurately to the site of pathology. The site of the symptoms often corresponds to the site of pathology, unlike in other systems such as the abdomen. For example, medial joint tenderness after a twisting injury to the knee consistently localizes the site of pathology to the medial meniscus or the medial collateral ligament of the knee. Similarly, sciatica with paraesthesia in a left L5 nerve root distribution indicates a left L5 disc protrusion.

The sequences used must be appropriate to visualize the pathology that is suspected (and that is mentioned on the request form). When examining the images, it is essential to know the normal anatomy of the site that is being imaged.

An area with high T2 signal on a fat-suppressed sequence is often a marker for the site of the primary pathology. High T2 signal in an area that is normally intermediate to low signal is a sign of oedema and haemorrhage. This signal will be centred on the site of pathology or adjacent to it. For example, in axial fat-saturated T2-weighted images of the knee, high T2 signal in the medial retinaculum indicates oedema and haemorrhage in this ligament and implies a patellar dislocation.

High T2 signal within the bone marrow on fat-suppressed sequences is also a sign of oedema, haemorrhage and microfractures. This occurs as a result of direct or repetitive injury to the area. The pattern of bone oedema can be indicative of the injury process. For example, anterior cruciate ligament tears are associated with bone marrow oedema at the anterior part of the femoral condyles and the posterior part of the tibial plateau. Similarly, patellar dislocation has a typical marrow oedema pattern at the medial facet of the patella and the lateral surface of the lateral femoral condyle that is caused as the patella dislocates, impinging laterally on the lateral femoral condyle.

Correlation of high signal on fat-suppressed T2-weighted sequences with low signal on T1-weighted sequences is important to remove the influence of artefact.

As a general rule, pathology should also be seen on at least two slices, as well as in two orthogonal planes.

ARTEFACTS IN MUSCULOSKELETAL MRI

Magic angle effect

This is seen in structures containing ordered fibres of collagen, such as tendons. There is an artefactual increase in T2 signal within the tendon when it passes 55° to the magnetic field. This artefact is seen for example in the extensor pollicis longus tendon of the wrist and the peroneus longus tendon of the ankle.

Chemical shift artefact

This is seen in gradient echo (GRE) sequences. Fat and water go in and out of phase with one another, depending on the echo time (TE). At a magnetic field of 1.5 T, the period of this alteration is about 4.4 s. Tissues containing both fat and water at the boundaries of structures are prone to this artefact, which manifests itself as a dark rim around the structures (Figure 1.1). GRE techniques are used in imaging of the cervical spine or in the knee, and the chemical shift artefact is seen around muscle fascicles.

Magnetic susceptibility artefact

This occurs at the interface between structures with different magnetic characteristics. There is low signal at the interface. Susceptibility artefact is especially evident when ferromagnetic materials are present, resulting in field distortions. Although susceptibility artefact can occur in any type of sequence, GRE sequences are most prone and are therefore used for its identification. This is especially important in identifying haemorrhage. From

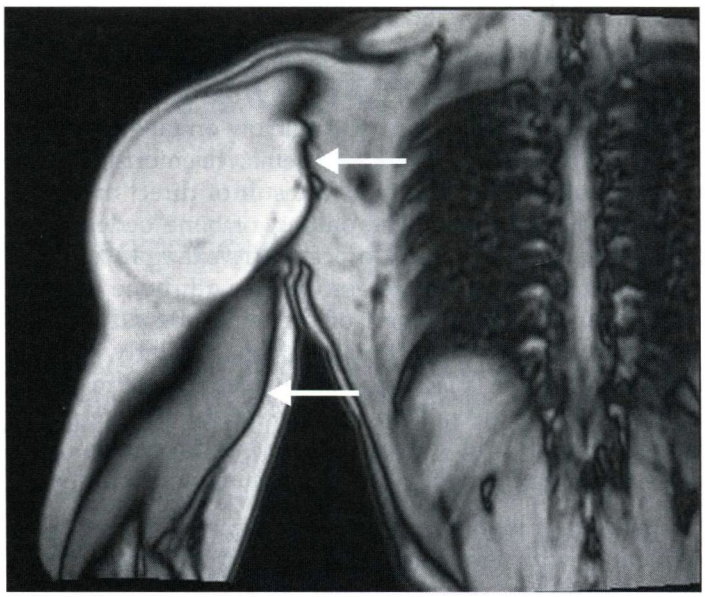

Figure 1.1 Chemical shift artefact at the interface between fat and muscle (predominantly water) in a GRE scout image of the shoulder.

the signal characteristics, the types of blood breakdown products can be identified (Figure 1.2) and the age of the haemorrhage can be estimated. This technique is used extensively in neuroimaging for assessing the age of cerebral haemorrhage. In musculoskeletal MRI, the use of susceptibility artefact is limited to identifying haemorrhage versus oedema.

Metal artefact

Misregistration is the main artefact from metal in sites such as total hip and knee replacements (Figure 1.3) and spinal metal work. This artefact is represented by geometric signal alteration in the frequency encoding direction. The dimensions of the artefact depend on the field strength, the direction in which the metal implant lies in relation to the magnetic field, the magnetic field strength and the bandwidth. Higher field strengths, smaller bandwidths and implants lying perpendicular to the magnetic field tend to worsen the artefact.

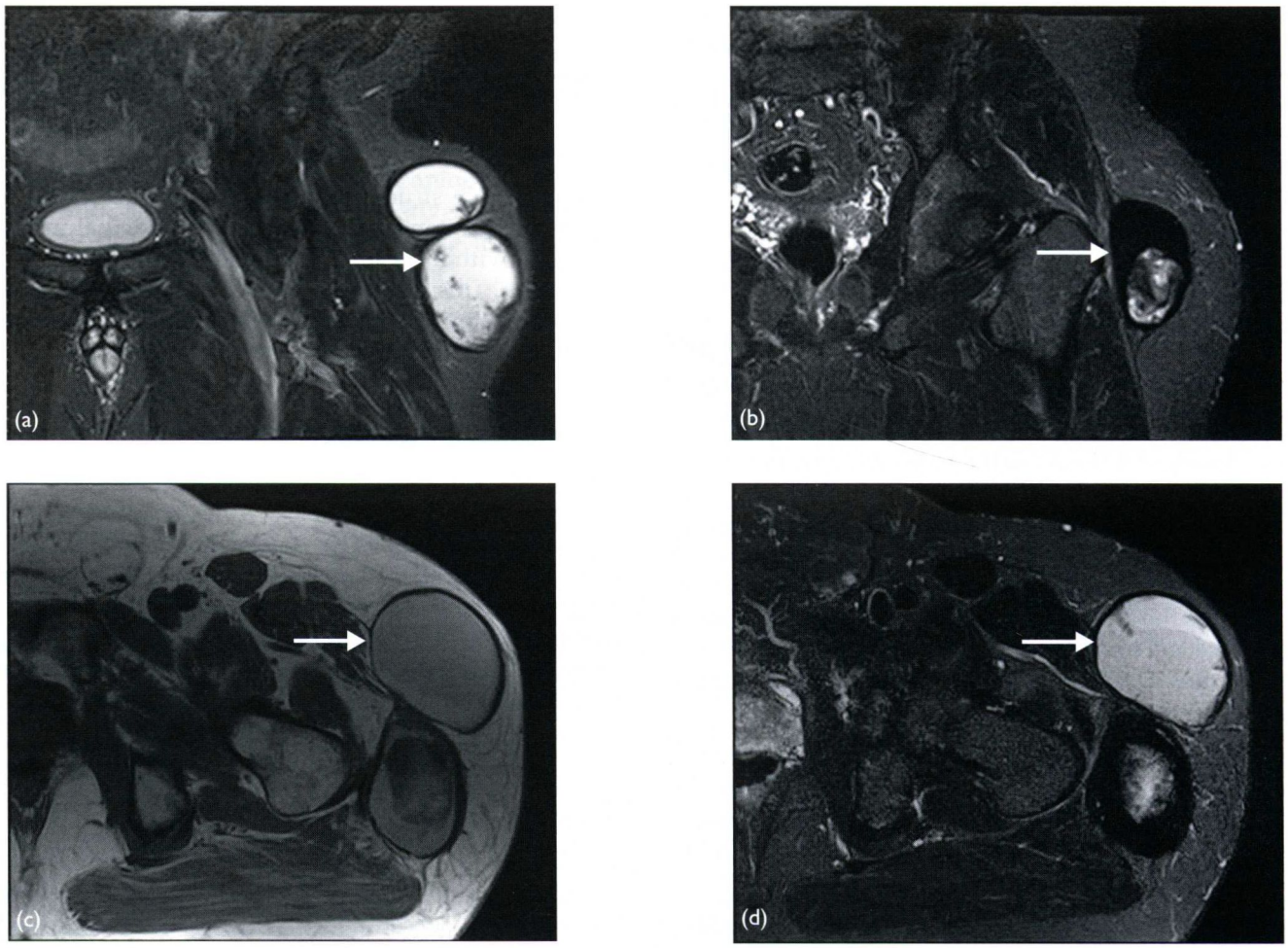

Figure 1.2 Magnetic susceptibility artefact in a resolving left thigh haematoma. In the PD-weighted fat-saturated (FS) image (a) and the T2*-weighted FS image (b), the black rim is consistent with haemosiderin deposition and the high signal is consistent with the presence of other blood products. In the axial T1- and T2*-weighted FS images (c, d), the low-signal rim is consistent with haemosiderin and the high-signal fluid is consistent with extracellular methaemoglobin. The axial T2*-weighted image (d) shows layering of blood products.

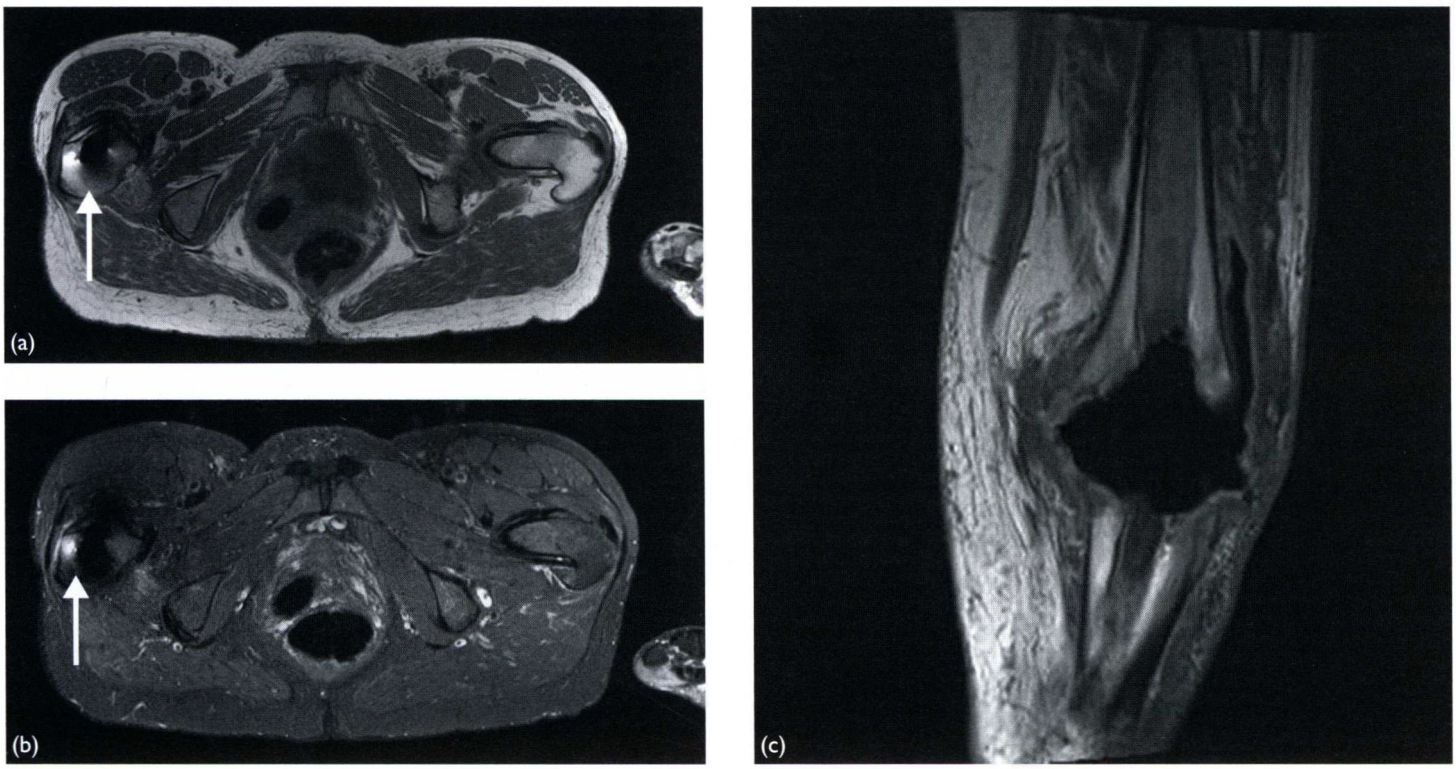

Figure 1.3 (a, b) T1-weighted and fat-saturated T2-weighted sections showing metal artefact from a total hip replacement. (c) Coronal T1-weighted image of a total knee replacement showing complete signal loss.

A number of approaches can be adopted to reduce metal artefact. These include lowering the field strength, broadening the receiver bandwidth, increasing the frequency encoding strength and orientating the implant so that it lies parallel to the main magnetic field.

Some sequences are more prone to metal artefact than others. Using STIR for fat suppression and FSE with short TE have been found to reduce artefact due to metal.

With the advent of the new metallic artefact reduction sequence (MARS), MRI has come to have a very important role in evaluating prosthetic joints, enabling a comprehensive assessment of articular and non-articular pathologies.

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Naraghi AM, White LM. Magnetic resonance imaging of joint replacements. *Semin Musculoskelet Radiol* 2006; **10**: 98–106.

2 THE SPINE

SPINAL IMAGING

Protocols

The spine is imaged in segments depending on the site of the symptoms.

Phased array coils help to improve both spatial resolution and signal-to-noise ratio. The drawback to this is the need for smaller fields of view, and hence multiple coil placements are necessary for imaging the whole spine.

Whole-spine imaging is used in:

- trauma
- metastatic infiltrates
- seronegative spondyloarthropathies such as ankylosing spondylitis
- spinal malformations

Key sequences

- T1-weighted fast spin echo (FSE) sagittal and axial (Figure 2.1a, c)
- T2-weighted FSE sagittal and axial (Figure 2.1b, d)
- Short-tau inversion recovery (STIR) sagittal and axial

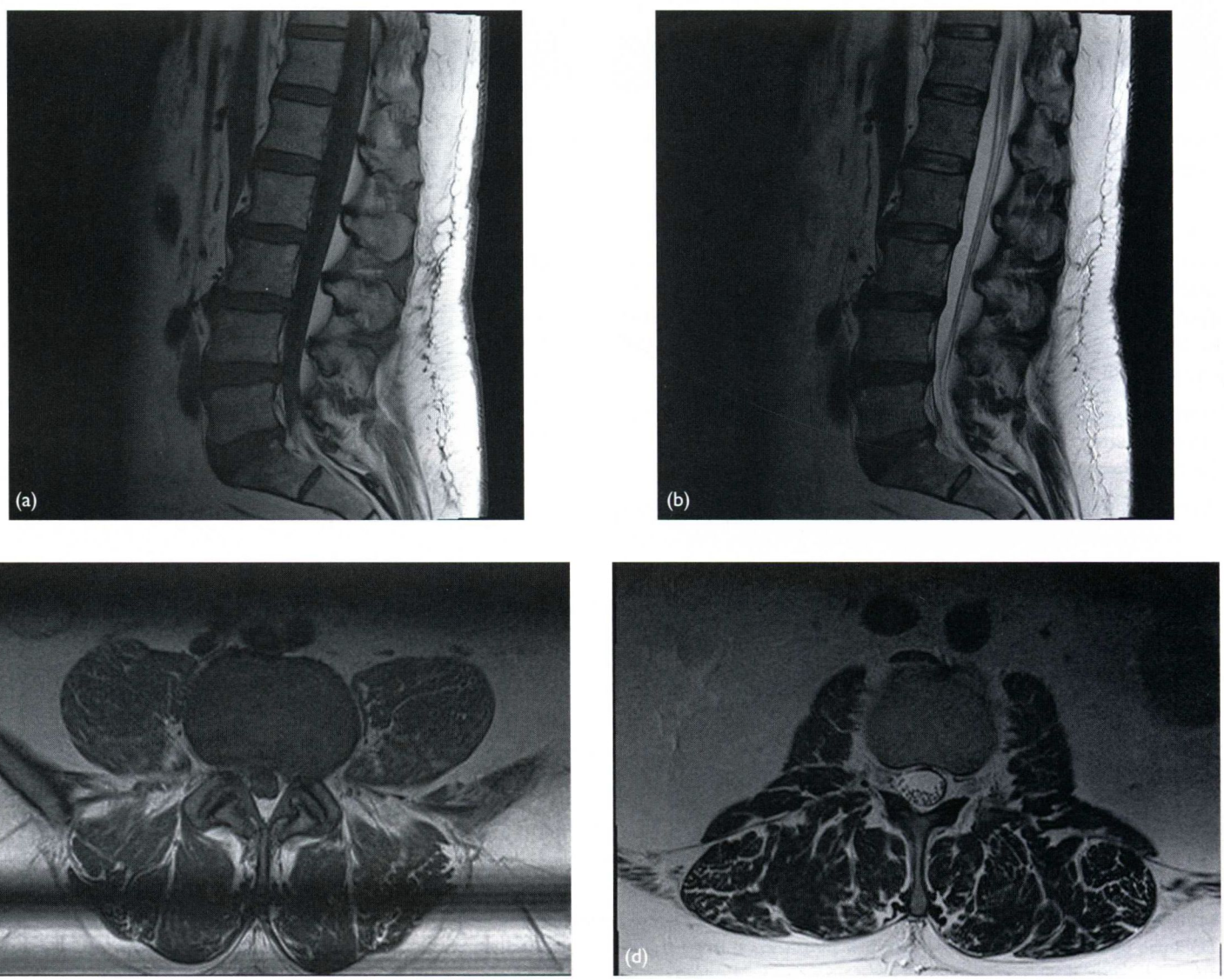

Figure 2.1 Normal lumbar spine sequences: (a) T1-weighted sagittal; (b) T2-weighted sagittal; (c) T1-weighted axial; (d) T2-weighted axial.

Gadolinium

If infection, a spinal cord mass or syrinx is suspected, gadolinium (Gd) is administered and images are obtained using a T1-weighted sequence with fat saturation.

SPINAL ANATOMY

See Figure 2.2.

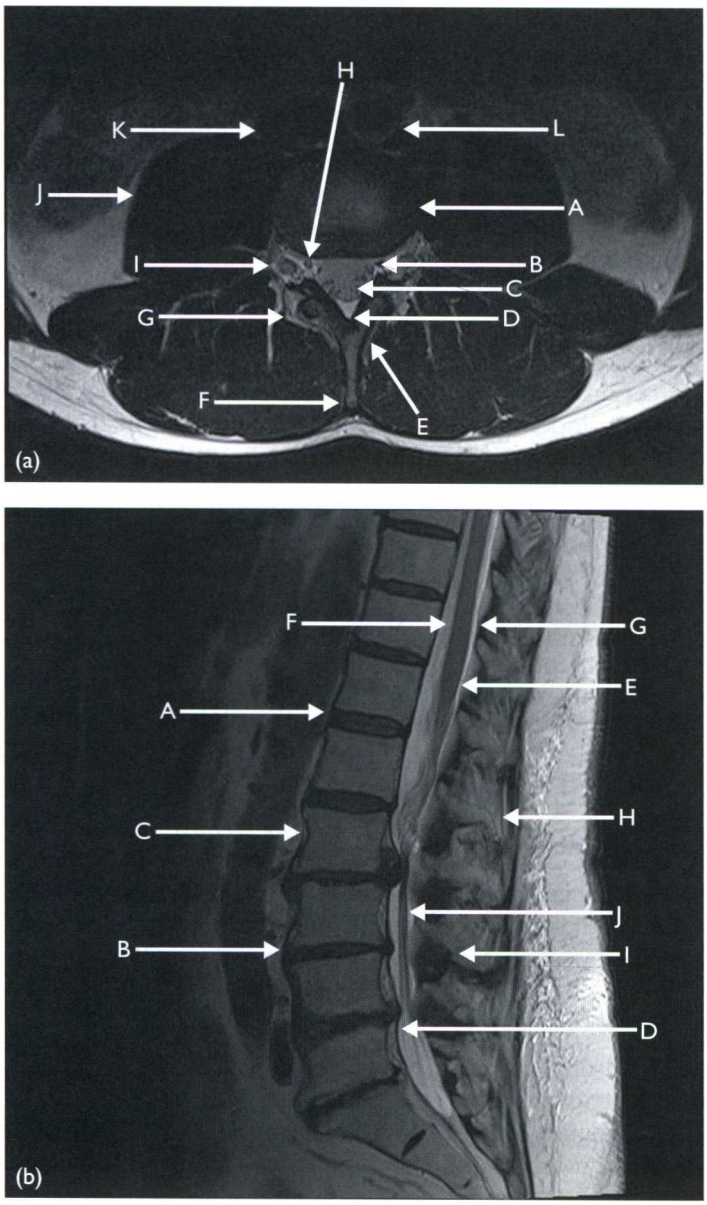

Figure 2.2 (a) T2-weighted axial section through the lumbar spine: A, intervertebral disc; B lateral recess; C, spinal canal; D, epidural fat; E, lamina; F, spinous process; G, facet joint; H, traversing nerve roots; I, exiting nerve roots; J, psoas muscle; K, inferior vena cava; L, aorta.
(b) T2-weighted sagittal section through the lumbar spine: A, intervertebral disc with high signal indicating a hydrated disc; B, dehydrated disc with uniform low signal; C, anterior longitudinal ligament; D, posterior longitudinal ligament; E, conus medullaris; F; spinal canal; G, epidural fat; H, spinous process; I, facet joint; J, cauda equina.

Vertebrae

The vertebral column is made up of 33 vertebrae that differ depending on the anatomic area.

There are seven cervical vertebrae, each with a body and a posterior arch consisting of two pedicles. Each pedicle has superior and inferior facets that articulate with corresponding superior and inferior vertebrae. The facet joints are synovial joints. In addition, there are lateral ridges of bone called the uncinate processes that articulate with the inferior aspect of the vertebral body above to form the uncovertebral joints. These are not true joints.

The C1 and C2 vertebral bodies are unique in their anatomy and provide the main support and pivot for the skull. The atlanto-occipital joints and atlanto-dens joints are both synovial in nature and are important sites in imaging of inflammatory arthropathies.

The thoracic vertebrae are anatomically typical. They have additional attachments to the ribs. The lumbar vertebrae are square-shaped with inferiorly angled spinal processes and, more importantly, neural foramina. This anatomic variation in the vertebrae results from the incongruent growth of the vertebrae and the spinal column. The spinal cord is fully formed at birth and grows at a slower rate than the vertebral column.

Nerves

There are eight cervical nerve roots, which exit the foramina above their respective vertebral bodies; thus the C1 nerve root exits between the occiput and the C1 vertebra and the C8 nerve root exits through the C7/T1 neural foramen.

The T1 and subsequent thoracic nerve roots exit inferior to the corresponding vertebral body; thus the T4 nerve root exits below the T4 pedicle, and so on. Because of the growth of the spinal cord and the vertebral column, the nerve roots become progressively more vertical through the thoracic and lumbar regions. The spinal cord typically ends at T12 and L1 as the conus medullaris, from which descend the filum terminale and the cauda equina. If the conus is seen to extend beyond this point then the question of a tethered cord arises. Ideally, every spinal MR examination should comment on the level of the conus.

The lumbar nerve roots also exit below their corresponding vertebrae.

The dural coverings of the spinal cord and nerve roots are in continuity with the dura in the cranial cavity. The dura and arachnoid are closely adherent to one another, while the pia mater is adherent to the spinal cord. The epidural space is a potential space between the dural and arachnoid membranes and is important to assess when imaging in the context of infection or tumour spread. The cerebrospinal fluid (CSF) circulates within the spinal canal and is in continuity with the circulating CSF in the cranial cavity.

In addition, the spinal canal has a specific configuration in the lumbar region. The lumbar and sacral nerves run parallel within the canal. The exiting nerve root runs down diagonally and through the corresponding neural foramen. The nerve is outlined by fat as it exits the foramen. The subsequent nerve root lies within the most lateral part of the dural sac. This part is known as the lateral recess and the nerve root is termed the traversing root.

Bone marrow

The MRI appearance of vertebral marrow depends on the pulse sequence and the relative amount of cellularity, protein, water and fat within the marrow. In an adult on a T1-weighted image, the yellow (fatty) marrow is isointense to subcutaneous fat. On a T2-weighted image, fatty marrow is usually higher signal than muscle and slightly lower signal than subcutaneous fat.

Changes with age may render bone marrow patchy. Uniform bone marrow change affecting multiple vertebrae is a subtle sign that may indicate marrow pathology and is case-specific. The endplates are made up of cortical bone and are low signal. With aging and changes in axial loading, the endplate signal can change. This appears as differences on T1- and T2-weighted imaging and is graded into three types according to the Modic classification (Table 2.1).

Table 2.1 Modic classification of vertebral body bone marrow changes

Modic type	T1-weighted imaging	T2-weighted imaging	Type of change
1	↓	↑	Oedema
2	↑	↓	Fatty change
3	↓	↓	Sclerosis

Discs and ligaments

The intervertebral discs are intermediate to high signal on T2-weighted imaging and low to intermediate signal on T1-weighted imaging. This is dependent on their degree of hydration and is an important sign to look for, since dehydration is an indicator of degeneration. The vertebral bodies are bounded by the anterior and posterior spinal ligaments, which are low signal on both T1- and T2-weighted imaging. These are best seen on sagittal images. The interspinous ligament is patchy in signal, with striations; this is due to its plane being parallel to the scan plane. The supraspinous ligament is also low signal on both T1- imaging and T2-weighted imaging. Finally, the ligamentum flavum is best seen on axial images and is the thickest ligament. This is seen as intermediate signal on T1- and T2-weighted imaging, owing to differences in chemical composition.

PRACTICAL POINTS

Artefacts

Motion artefact is responsible for many of the technical errors: patient and physiological artefacts from lung, cardiovascular and bowel motion, as well as artefacts due to CSF flow. CSF pulsation artefact is particularly seen on T2-weighted imaging.

A second type of artefact is the truncation or Gibb artefact seen at interfaces of high contrast (e.g. CSF and spinal cord). Seen on sagittal imaging, this may simulate a syrinx. Syrinx may be differentiated from tumour and Gibb artefact by enhancement characteristics.

With increasing use of spinal instrumentation, there is an added problem of susceptibility artefact from the metal. This may obscure the spinal cord and render images non-diagnostic.

Review areas

On cervical spine MRI, review areas include the cerebral contents and the cervical lymph node chains in the field of view. Comment should be made about the craniocervical junction and level of the tonsils (Chiari malformations may be associated with cervical pathology).

The common review areas in the lumbar and thoracic spine are:

- the paravertebral soft tissues
- the aorta for aortic aneurysms
- soft tissues of the back for soft tissue masses

SPINAL TRAUMA

Introduction

MRI of the spine is used to look at soft tissue injuries associated with spinal fractures. In addition, some fractures are also seen well on MRI. The MRI scan is done after conventional radiography of the cervical spine and CT scans for vertebral fractures.

MRI is useful to look for ligamentous injury and traumatic disc protrusions and to examine the cord itself. This examination should ideally be performed within 3 days of the trauma, since the initially high signal from oedema and blood products will decrease over time.

Key sequences

- Whole-spine (non-contiguous spinal trauma is seen in 10–15% of cases)
- T1-weighted axial and sagittal
- STIR axial and sagittal
- GRE (which may identify blood products within the cord)