2.1 Introduction

All imaging techniques have one feature in common: the basis is the interaction between energy and matter. This applies even to a conventional photograph: light (electromagnetic radiation in the visible wavelength spectrum) is reflected with different frequencies (colours) and intensities (brightness) from the surface of an object, thus, producing an image visible to our eyes. This image can then be reproduced on photographic film by a camera, or captured on canvas by an artist.

In a medical diagnostic setting, ultrasound waves can be reflected from tissue interfaces within the body to produce an echographic image. Electromagnetic energy in the high-energy X-ray part of the spectrum is capable of passing through the human body but is not entirely unaffected: the X-ray photons are weakened (attenuated) to a varying degree depending on their wavelength (hardness) on the one hand, and the electron density and thickness of tissues within their path on the other. The residual radiation which has passed through the body is registered by an X-ray film or another type of photon detector, and the distribution of grey shades (contrast) in the resulting image represents local variations in the tissue density.

Besides being reflected from, or transmitted through the body, energy can also be emitted from the body itself, for instance, by injecting a substance containing a radioactive isotope into the body. This principle is the basis of nuclear medical imaging techniques.

Another emission-based technique is magnetic resonance imaging (MRI), in which the protons incorporated in water molecules of the body tissues emit radiofrequency (RF) signals under the influence of a combination of a magnetic field enclosing the body and RF energy which is beamed into the body from an external source, causing the protons to “resonate” in electromagnetic terms.

All techniques presently employed for spinal imaging have shortcomings. Conventional X-ray images have the drawback that potentially harmful radiation is employed, in addition to possessing a limited contrast resolution. In the early decades of the last century, various methods were developed to artificially enhance image contrast by injecting contrast substances with very low (air) or high radiographic density (usually iodinated fluids) into various soft tissue structures or compartments. In the spine, myelography is the best known of these techniques.

The development of new diagnostic methods, such as computed tomography and magnetic resonance imaging, has resulted in a dramatic improvement in low-contrast resolution, coupled with the advantages provided by sectional (tomographic) imaging. The downside is an increase in irrelevant detail demonstrated by these improved techniques. This applies particularly to spinal imaging. Even conventional X-ray films of the spine often demonstrate age-related and degenerative changes which are not necessarily associated with the presence of disease. An MRI study can present an even greater abundance of morphologic details whose pathologic relevance is unclear. False-positive interpretation of an incidental finding is an ever-present pitfall in all imaging studies, and this is especially the case when insufficient attention is paid to the correlation of high-resolution CT and MR imaging findings with clinical signs and symptoms.

2.2 Conventional X-ray Studies

Plain films of the spine offer a quick and inexpensive evaluation of bony structures and are frequently used as an initial screening examination in, for instance,
suspected fractures, malalignment, and congenital spinal defects. Abnormal spinal curves can be assessed in scoliosis and the anatomy of individual vertebrae can be defined, although superimposition of anatomical structures is a problem. Spondylosis and spondylolisthesis are well demonstrated. Spinal metastases can be detected on plain X-ray films, but only in a late stage, when cortical bony structures of the vertebrae are affected, or the vertebra is deformed or collapsed. Manifestations of spondylodiscitis are also detected relatively late.

At present, plain film spinal imaging is still ordered frequently in patients presenting with low back pain and neck pain, but the diagnostic value of the examination in the evaluation of such complaints is low. Contrast resolution in conventional X-ray images is limited: only four tissue densities, namely bone, water, fat, and air, can be distinguished and soft tissue pathology such as a disc herniation cannot be visualised. On the other hand, so-called degenerative features such as disc space narrowing, spondylosis, and spondylarthrosis can be demonstrated in asymptomatic as well as symptomatic individuals (Fullenlove and Williams 1957).

The diagnostic yield of plain film studies in low back pain is very limited unless so-called red flags (indicators for specific disease conditions such as neoplasm, disc herniation or infectious disease) are present (Staiger et al. 1999). As mentioned above, however, the sensitivity for early detection of specific pathology by plain films is low, and in such cases alternative techniques with higher sensitivity, such as CT or MRI, are preferable.

A plain film examination of the lumbar spine usually consists of a lateral and a postero-anterior view. Oblique views are sometimes performed of the isthmus region in case of spondylolisthesis, but these substantially increase the X-ray dose to the patient, and are not always necessary. Studies of the spine in flexion (kyphosis) and extension or retroflexion (lordosis) can be used in the assessment of post-traumatic or degenerative instability.

2.2.1 Contrast Studies:

The following conventional X-ray studies featuring contrast injection are presently still performed in the lumbar sacral spine:

**Lumbar myelography** (syn. radiculography, caudography). In this examination an iodinated radiologic contrast fluid is injected into the dural sac so that the cerebrospinal fluid is opacified, outlining the dural sac, the dural root sleeves and their contents (Bates and Ruggieri 1991). Structures of interest are the conus medullaris of the spinal cord, whose tip is located approximately at the L1–2 level, and the nerve roots forming the cauda equina which originate from the conus medullaris and traverse the lumbar dural sac in cranio-caudal direction. These nerve roots exit the dural sac by way of a dural root sleeve which accompanies the emerging dorsal and ventral root fibres over a variable distance (see Chap. 3). Lumbar disc herniations which are located in the central, paracentral and subarticular regions of the spinal canal (see Chap. 4) can produce impressions upon the dural sac and displacement of the intradural nerve roots, as well as cut-off of contrast filling of the root sleeve (Fig. 2.1). Sometimes also swelling of the nerve root proximal to the site of compression is seen. The myelographic image of the nerve root ends when it leaves the contrast-filled subarachnoid space. Thus, lateral disc herniations compressing the dorsal root ganglion or nerve ramus inside or outside the intervertebral foramen, and which are reported to occur in around 10% of cases, (Abdullah et al. 1988), will frequently be missed by myelography (Jackson and Glah 1987).

Contrast myelography is not a very invasive procedure, but it is not completely innocuous (Bates and Ruggieri 1991; Wilmink et al. 1984). Even in experienced hands, a lumbar puncture followed by injection of contrast fluid may be difficult and painful, especially when the dural sac is constricted or collapsed and the nerve roots are crowded together by a large herniation or by narrowing of the spinal canal at the puncture site. The iodised oils which were initially employed for myelography frequently gave rise to adhesive arachnoiditis resulting in crippling back complaints. The water-soluble contrast media which were later introduced produced better images of the root sleeves but the first generation of these agents possessed a high osmolality and neurotoxicity and could also cause adhesive arachnoiditis (Skalpe 1978). Modern low-osmolality contrast media do not share these severe side effects.

Nowadays, the most common indication to perform contrast myelography is when MRI is contraindicated or not available, and when CT does not provide an
2.2 Conventional X-ray Studies

adequate image of the dural sac and of possible intradural pathology. In these cases the conventional myelographic study will almost invariably be followed by CT myelography (see below).

Myelography can be employed to produce images of the dural sac and the cauda equina in the upright posture, or in lumbar flexion and extension (Penning and Wilmink 1981).

Discography. This examination technique is employed primarily to localise painful intervertebral discs responsible for lumbago or low back pain, and not to diagnose lumbosacral nerve root compression causing sciatica. A water-soluble iodinated radiologic contrast medium is injected into the nucleus pulposus of the intervertebral disc. The purpose of this is twofold. Firstly the increase in intradiscal pressure caused by the injection may reproduce or exacerbate the patient’s pain complaints, thus confirming that the disc in question is the source of the pain. Secondly, X-ray images can show penetration of the contrast medium into fissures and defects in the annulus fibrosus, and sometimes also into herniated disc material (Fig. 2.2). Disc herniations and nerve root compression are diagnosed more accurately by MRI and CT however.

Discography is a controversial diagnostic procedure, with outspoken proponents as well as antagonists. The examination can be tedious and unpleasant for the patient, especially when multiple disc levels are studied. Discography is used to localise painful discs, but there are reservations because false-positive pain responses can occur, even when care is taken to apply a low injection pressure (Carragee et al. 2006), and
subjective pain responses at discography should be interpreted with special caution in patients with chronic pain, social stressors and psychological disturbances (Carragee and Hannibal 2004). Annular tears or fissures can be demonstrated by discography, but MRI has shown these to occur in asymptomatic individuals as well as in low back pain sufferers with painful discs (Stadnik et al. 1998).

Two other contrast examinations, peridurography and epidural venography are no longer performed. These techniques relied on opacification of the epidural space itself, or the veins in this space respectively, by contrast injection, either directly into the spinal canal via the sacral hiatus (Luyendijk and van Voorthuisen 1966) or into the paraspinal and intervertebral veins via catheterisation of the iliac veins (Wilmink et al. 1978). The diagnostic principle of these methods was to demonstrate disc herniations by their compressive effect on the epidural structures, and thus provide an alternative to lumbar myelography. The contrast opacification was too irregular and unreliable however, and with the advent of newer imaging techniques these methods were relegated to obscurity.

### 2.3 X-Ray Computed Tomography

Computed tomography CT (Hounsfield 1973) revolutionised medical imaging by its introduction in the 1970s. Three innovations were combined:

- Acquisition of sectional (tomographic) images by the use of an X-ray tube rotating around the patient. This made it possible to study spinal anatomic relationships in the axial plane which could not previously be visualised. A much better insight was obtained in the morphology and classification of, for instance, spinal stenosis (see Chap. 4).
- Detection of smaller differences in X-ray attenuation (tissue density) by using more sensitive scintillation detectors instead of an X-ray film, thus, greatly improving soft tissue contrast resolution.
- Image reconstruction by a computer algorithm permitting selection of window and level settings appropriate for viewing bony or soft tissue structures as required.

The improved contrast resolution of CT made it possible to image disc herniations and other intraspinal normal and abnormal soft tissue features without the necessity of contrast injection into the dural sac (Fig. 2.4). Visualisation of intradural details by uncontrasted CT is limited; the spinal cord can sometimes be seen faintly, and intradural nerve roots not at all.

CT and myelography are complementary techniques: the first is more suitable for assessing the cause of radicular complaints, herniated disc, spinal stenosis etc., while the second is better for imaging the effect, the compressed intradural nerve root (Wilmink 1989). Techniques which combine both these features are CT myelography and MRI with MR myelography (see below).

CT can also be combined with discography to produce CT discographic images, thus improving the sensitivity with which small annular tears can be detected.

The sensitivity of CT for bony vertebral pathology such as metastasis and fracture is better than that of plain films.

A significant development has been the introduction of multi-slice spiral CT scanning with multi-planar reformattting. This technique permits rapid scanning of a large tissue volume by a thin continuous spiral or helical section, and this has proven to be of special value, for instance, in case of spinal trauma where subtle fractures and dislocations, especially in the posterior spinal elements, can be detected with an ease and accuracy unrivalled by any other imaging method.

CT can provide an acceptable diagnostic alternative to MRI in many cases with disc herniation or spinal stenosis (Figs. 2.3, 2.4). Soft tissue resolution by CT, however, is less than when MRI is employed, and some disc herniations can be overlooked (see Sect. 2.4). Anatomical detail is also less in reformatted sagittal CT images when compared to direct sagittal MRI cuts; in addition bone marrow pathology annular fissures and other subtle changes cannot be detected by CT. Intraspinal details usually are less well-depicted by CT at the level of the vertebral pedicles and lamina, where the dural sac is entirely surrounded by a ring of bony structures (see Chap. 3), where there is little epidural fat to outline the dural sac and migrated disc fragments may be missed. At the disc level the structures bordering the spinal canal are ligamentous and less dense, and there is usually more intraspinal fat present to act as a natural contrast agent.

CT has for many years formed the mainstay of diagnostic imaging in patients with radicular pain and related conditions, despite the drawback that compression of the intradural nerve root could not be visualised directly.
Indirect evidence of compression of the intradural root in non-myelographic CT images can be derived from features such as flattening of the ventrolateral angle of the dural sac at disc level, as well as displacement by the herniation and disappearance of the epidural fat adjacent to the dural sac (Wilmink 1989).

Fig. 2.3 Spiral CT study with multiplanar reformat. Patient with L4–5 disc herniation (a) mid-sagittal reformat showing extrusion migrating below disc level (arrow), axial 2 mm cuts at level of posterior disc (b), L5 endplate (c), and L5 lateral recess (d) show extrusion migrating laterally towards right L5 root in lateral recess (arrow). Left L5 root normally outlined by fat.
In order to limit the radiation dose, only the lower three lumbar disc levels are routinely scanned in suspected lumbar disc herniation and this involves a risk of missing a herniation which is situated at a higher lumbar level (see also Chap. 3).

CT slices can either be acquired in separate sets with the CT gantry angulated parallel to each disc, or as a continuous or overlapping series of parallel slices. The advantage of the first method is that there is less distortion of sagittal dimensions of the spinal canal, but the disadvantage is that portions of the spinal canal between the slice sets may be skipped, and migrated disc fragments in this region easily overlooked (Fig. 2.5).

Slice thickness in non-spiral lumbar CT is usually 3–5 mm, with thinner 2 or 1 mm slices preferred when spiral CT scanning with multi-planar reformatting is to be performed. The spiral datasets are acquired without gantry angulation.

### 2.3.1 CT Myelography

This technique which was first reported by Di Chiro and Schellinger (1976) is a useful adjunct to conventional myelography as well as to non-contrast CT. The presence of an intrathecal contrast medium makes it possible to clearly discern the spinal cord and individual nerve roots within the dural sac, which is not possible on non-contrast CT images. These structures are presented in the axial plane, which is not possible on conventional myelograms. The conventional myelographic image of the nerve root ends after its departure from the dural root sleeve, whereas with CT myelography the root can first be followed through the CSF compartment where it is outlined by the contrast medium in the
2.4 Magnetic Resonance Imaging (MRI)

Imaging by nuclear magnetic resonance (NMR) (Mansfield and Maudsley 1977), presently better known as magnetic resonance imaging or MRI, produces computed tomographic sections similar to X-ray CT, but makes use of a different imaging principle. In X-ray CT, image contrast is derived from differences in X-ray attenuation due to variations in electron density in various structures within the body. In MRI the protons of the body are induced to act as radiofrequency (RF) transmitters by being positioned in a magnetic field and subjected to RF energy directed from an antenna, or coil. The electromagnetic resonance of the protons is analogous to the resonance of a tuning fork when exposed to sound of the appropriate frequency. The RF signals from the protons can be manipulated or “weighted” to selectively amplify signal intensity of various substances and structures within the body, and are spatially encoded to produce an image.

An MR image in which contrast is dependent on differences in longitudinal magnetic relaxation times as defined by so-called T1 values between various tissues is called “T1-weighted”. When image contrast is predominantly determined by differences in transverse magnetic relaxation values (T2), the image is called “T2-weighted”.

For spinal imaging, MRI has significant advantages over CT: soft tissue contrast resolution is better (Fig. 2.7) and there are no artefacts due to high-density skeletal structures. The signal intensity of bony spinal structures is less bright in MR than in CT images, and the latter method is better for diagnosing bony cortical lesions such as in vertebral fractures. Although some consider that spinal stenosis is better demonstrated by CT than by MRI, in fact cortical bone can be well-distinguished as a dark line bordering the brighter bone marrow in T1-weighted MR images. Also, spinal stenosis has an important ligamentous as well as a bony component. Even in cases with severe developmental stenosis, compression of the dural sac and the cauda equina takes place mainly at the level of the intervertebral disc, and is not due only to bony narrowing of the spinal canal but rather to superimposed ligamentous encroachment by bulging of the annulus fibrosus and hypertrophy of the flaval ligaments (Fig. 2.8, see also Chap. 4, Fig. 4.1.b and d), and

arachnoid space, then more distally through the foramen and beyond, where it is outlined by fat (Fig. 2.6).

When MRI is not available or contraindicated, CT myelography can be used for the detection of intraspinal space occupying lesions: intradural (intramedullary neoplasm or cyst, extramedullary meningioma or nerve root tumour) extradural (disc herniation, intradural neoplasm or extradural hematoma) or both (dumbbell schwannoma). Cord atrophy or transection can also be demonstrated, but spinal cord lesions without mass effect, such as cord infarct or multiple sclerosis plaques can only be visualised by MRI. Other drawbacks of CT myelography compared to MRI are the necessity for intrathecal contrast injection and the employment of ionising X-rays.

On the other hand, spatial resolution in CT myelographic images is usually better than in axial MR images, and this is especially important in diagnosis of nerve root compression, for instance in the lateral recess of the spinal canal, where MRI often does not provide sufficient detail. CT is more accurate than MRI for the assessment of calcified herniations as well as bony spurs emanating from the vertebral bodies or encroaching upon the foramen as well as for demonstrating the presence of gas in a degenerated disc or joint (see Fig. 4.18).
Fig. 2.7 CT compared to MRI. CT and MRI of same large L4–5 disc extrusion. Axial 5 mm CT section (a) shows apparently normal L4–5 disc. Axial T1-weighted 4.5 mm MRI section (b) shows large extrusion almost completely collapsing dural sac (arrow), also well-depicted in sagittal T₁-(c) and T₂-weighted images (d). Note that in retrospect remnant of collapsed dural sac is very faintly visible on CT section.
Fig. 2.8 T1-weighted axial MR image (a) in patient with localised narrowing of spinal canal at L4–5 showing almost complete CSF block on sagittal images (b, c) best seen on T2-weighted image (c). Note that axial cut clearly shows bony details such as facets on the one hand, as well as soft tissue structures such as annulus fibrosus (arrow) and flaval ligament (arrowhead) on the other.
sometimes deformation of the spinal canal by degenerative anterolisthesis.

Subtle changes in shape and composition of the spinal cord can be demonstrated by MRI, and intradural nerve roots can be seen without the necessity for contrast injection into the dural sac (MR myelography, see below). MR images can be acquired in any plane desired, and are superior to reformatted sagittal or coronal CT images of the spine, especially for showing soft tissues.

The largest single indication for spinal MR imaging is presently in degenerative spinal disease, usually performed to diagnose a possible disc herniation.

A number of options for lumbar spinal MR imaging will now be discussed. It will be clear that there are many methods to produce good-quality diagnostic spinal images (Ruggieri 1999), and the selection depends upon the characteristics of the MRI system employed and personal preferences of the radiological user and clinical end-user. An example of a typical set of imaging sequences for use in lumbar degenerative disc disease is given in Fig. 2.9.

The discussion of the various techniques set out below is not intended to be exhaustive, and reflects the personal experience of this author. For more detailed information regarding technical aspects of MR imaging and the various acquisition sequences mentioned below, the reader is referred to specialised texts dealing with these subjects. A review of recent developments in spinal MR imaging sequences is given by Vertinsky et al. (2007).

### 2.4.1 T1-Weighted (T1-W) Images

In these images the CSF-filled dural sac is darker than the disc and vertebrae (Fig. 2.9a). Normal adult bone marrow has a light grey shade, with somewhat brighter signal intensity than that of the intervertebral disc. The fat seen in the epidural pockets dorsal to the dural sac, in the sacral canal and in the intervertebral foramina has the highest signal intensity in T1-W images of the spine, and T1-weighting is popularly said to produce a “fat image”. In such images fat acts as a natural contrast medium, and structures bordered by fat are clearly outlined: dorsal and caudal borders of the lumbar dural end-sac, foraminal borders and intraforaminal contents such as dorsal root ganglia, as well as laterally migrated disc extrusions.

Due to the low signal intensity of CSF on T1-W images, the intradural nerve roots can only be faintly distinguished. The spinal cord can be seen, but not as well as in T2-W images. The lack of contrast between the posterior disc surface and the anterior border of the dural sac, both dark, sometimes makes it difficult to discern disc herniations in this location on T1-weighted images.

In the lumbar spine T1-W images are usually acquired by a so-called spin-echo (SE) or fast spin-echo (FSE) sequence.

### 2.4.2 T2-Weighted (T2-W) and T2*-Weighted (T2*-W) Images

The bright signal intensity of water (CSF, nucleus pulposus) predominates in images with T2-weighting, and these are sometimes known as “water images” (Fig. 2.9b). For this reason intradural features such as spinal cord and cauda equina are best seen with this technique, as are disc herniations impinging upon the CSF-filled dural sac or the root sleeve.

T2-W lumbar spinal images are at present generally acquired with a 2D fast spin-echo, syn. turbo spin-echo (FSE, TSE) sequence. Conventional spin-echo (CSE) sequences are no longer routinely used because of the lengthy scanning times necessary to produce sufficient T2-weighting with this technique. CSE and FSE do not produce identical T2-weighted images; in a CSE sequence epidural fat and bone marrow fat have low signal intensity, while FSE produces a much higher fat surrounding CSF (white arrow), also of dorsal root ganglion in foramen by surrounding fat (white arrowhead). Borders of dural sac (small black arrows) are less well-defined, however (d). Right and left oblique MR myelographic images presenting 3D projections of dural sac acquired with single-shot, single-slice technique (see below). Note good depiction of intradural nerve roots and root sleeves. Vertebral structures not imaged due to heavy T2 weighting. 

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**Fig. 2.9** Images from normal lumbar spinal MRI examination at 1.5 T. (a) Mid-sagittal 4 mm T1-weighted spin-echo image showing bright signal from epidural and subcutaneous fat, dark CSF signal. (b) Mid-sagittal 4 mm T2-weighted fast spin-echo image showing bright fluid signal from CSF and nucleus pulposus, also from epidural and subcutaneous fat. Note better depiction of posterior disc contour compared to (a). (c) Axial 4 mm T2-weighted fast spin-echo image at L4–5 produced with 3D DRIVE technique. Note good depiction of intradural cauda equina fibres by surrounding CSF (white arrow), also of dorsal root ganglion in foramen by surrounding fat (white arrowhead). Borders of dural sac (small black arrows) are less well-defined, however (d). Right and left oblique MR myelographic images presenting 3D projections of dural sac acquired with single-shot, single-slice technique (see below). Note good depiction of intradural nerve roots and root sleeves. Vertebral structures not imaged due to heavy T2 weighting.
signal. In FSE T2-weighted images epidural and foraminal fat may be almost iso-intense to CSF (Fig 2.9b, c). This has the advantage that extradural disc fragments in the intervertebral foramen are well-outlined by bright fat; almost as well as in T1-W images. One could say that FSE T2-W images provide “water contrast” as well as “fat contrast”. The disadvantage of this is that the CSF-filled dural sac can be difficult to distinguish from the surrounding epidural fat, as both are now bright (Fig. 2.9c). This can create a problem when assessing, for instance, abnormal increase in epidural fat (lipomatosis) on T2-W FSE images (see Chap. 4). In addition, bone marrow lesions with high water content, such as in certain degenerative changes, metastases or osteomyelitis, which classically appear hyperintense to normal bone marrow in a T2-weighted CSE image, may be almost invisible on T2-weighted FSE images because the normal fatty bone marrow is now iso-intense to the lesions. Application of fat-suppression can be useful here (see below).

An FSE T2-W 3D driven equilibrium technique (DRIVE) presently used in our department for axial spinal imaging employs a desaturating pulse after acquisition of the spin-echo, in order to null residual magnetisation and so reduce the repetition time. In this way heavy T2 weighting can be produced in a rapid acquisition (Fig. 2.9c).

An alternative option for producing “water images” is by the use of a T2*-weighted gradient-echo (GRE) sequence which also produces a high water signal. This technique is sometimes used for axial spinal imaging, most frequently used for axial spinal imaging.

**Fig. 2.10** Comparative axial images acquired by T1 SE, T2 DRIVE, and T2*BFFE techniques respectively. (a1–3) Case with conjoint left L5 and S1 root sleeves. T1-weighted image (a1) shows no intradural detail due to low CSF signal. Dural sac, root sleeves and foraminal details well-depicted due to high fat signal. T2-weighted DRIVE image (a2) produced by FSE sequence giving high CSF signal as well as high fat signal shows good depiction of intradural nerve roots as well as dorsal root ganglia in foramina. Outline of dural sac less well shown, however. T2*-weighted BFFE image (a3) produced with gradient-echo sequence shows good depiction of dural sac, root sleeve and intradural nerve roots, but foraminal structures are less well shown. Spurious image of L3–4 disc protrusion (arrowheads) shown in T1-weighted image (b1), not shown in T2-weighted DRIVE image (b2) and T2*-weighted BFFE image (b3). Spinal nerve (arrow) well seen outlined by fat in (b1) and (b2), not in (b3)
Figure 2.10 shows a comparison of imaging features of three techniques for axial lumbar spinal imaging: T1-W fast spin-echo, T2-W DRIVE and T2*-W balanced fast-field echo (BFFE). We have found the second option the most useful.

2.4.3 Proton Density-Weighted (PD-W) Images

MRI is a highly versatile method for assessing various tissue characteristics and transforming these characteristics into image contrast. Beside producing images weighted for differences in T1 or T2 relaxation times, the MR acquisition sequence can be so arranged that neither of these two tissue parameters plays a significant role in image contrast; variations in signal intensity (brightness) producing image contrast now depend mainly on variations in proton density within the tissues. Ligamentous structures containing bound protons (ligaments, cortical bone) are then clearly discernible by their low signal intensity. Ruptures in ligamentous structures such as the outer annulus fibrosus are very clearly seen (Fig. 2.11) but this is the only especially useful diagnostic feature of proton density weighting and the technique is at present not routinely used in spinal imaging.

2.4.4 Fat-Suppressed Images

Suppression of bright fat signal in the MR image can be achieved in several ways. Short TI inversion recovery (STIR) is very effective in nulling the fat signal from epidural fat and bone marrow, and is helpful in the analysis of bone marrow signal changes (Fig. 2.12). Spectral fat suppression by pre-saturation (SPIR, fat-sat) can also be used in T2-W fast spin-echo sequences to produce the same effects.

Post-gadolinium T1-weighted images can be acquired with a spectral fat-saturation pre-pulse (SPIR or fatsat). This is useful when bright fat signal (bone marrow, epidural fat) is a hindrance to assessing contrast enhancement of vascular structures (Fig. 2.13), but also infectious or metastatic bone marrow enhancement, or enhancement of post-operative epidural scar tissue can be better identified in this way (see also Chaps. 4 and 5). STIR cannot be used in T1-W post-gadolinium MR imaging because the bright gadolinium signal is suppressed by this technique together with the fat signal.

2.4.5 MR Myelography:

The purpose of producing MR myelographic images is not to satisfy nostalgic feelings in elder colleagues but to provide a better diagnostic image of the intradural nerve root. The course of a traversing nerve root as it passes from the dural sac into the root sleeve in the lateral recess region of the spinal canal is often hard to follow in sagittal or axial MRI sectional images. Sagittal sections suffer from partial volume effects in the lateral recess region, and even thin axial cuts can fail to identify the root, especially when the lateral recess is not roomy. Individual cauda equina fibres can be discerned on thin (2mm)-section T1-weighted volume scans and traced over some distance in oblique reformats (Hofman and Wilmink 1995) but comparison of the aspect of a single nerve root and root sleeve with the contralateral root or the adjacent root above or below is not possible with flat sections through a curved tubular banana-shaped object such as the lumbar-sacral dural sac. Curved reformatted sections can be constructed but the production is time-consuming.

A presentation of a virtual 3D image of the dural sac and root sleeve allows a better assessment of the course of the root, and an easier comparison with adjacent and contralateral roots. MR myelographic images are generally acquired with heavy T2-weighting, which produces a very bright water signal from the CSF in the dural sac and (virtually) no signal from other spinal structures. The dural sac is then easily segmented by a maximum intensity projection (MIP) technique similar to that used in MR angiography, and presented as a virtual 3D object with the root sleeves well shown and the intradural roots visible as dark linear structures (Krudy 1992; el Gammal et al. 1995; Ferrer et al. 2004). This technique compares well with conventional contrast myelography; (Ramsbacher et al. 1997; Kuroki et al. 1998), and patient acceptance of an MRI study is better than is the case with conventional myelography (Albeck and Danneskiold-Samsoe 1995).

Figure 2.14 shows an example of adjacent oblique T2-weighted MRI sections fused to produce a virtual 3D representation of the dural sac and emerging root
Fig. 2.11 Imaging of annular rupture by proton density compared to T1-weighting. Midsagittal T1-(a) and proton density-weighted images (b) show extruded disc material behind intact L4–5 posterior longitudinal ligament. Lateral sagittal cuts through foramen with similar weighting (c, d) show ruptured annulus, more clearly in proton density weighted image (d) (arrow). Note small fragment of annulus displaced upwards into foramen (long arrow).
Fig. 2.12  Fat suppression in degenerative bone marrow changes. T1-weighted image (a) shows area of signal loss due to increase in bone marrow water content above L4 endplate (arrow); area of increased bone marrow fat signal below L5 endplate (thin arrow). T2-weighted fast spin-echo image (b) shows areas with increased fat as well as water content now hyperintense. STIR fat-suppressed image (c) confirms high water signal in bone marrow above L4 endplate indicating Modic type 1 degenerative changes; also suppression of fat signal from area below L5 endplate indicating Modic type 2 fatty degenerative changes here. Decrease in bone marrow fat signal combined with increase in water signal is seen in Modic type I changes but also in for instance metastasis or spondylitis. Follow-up in this case revealed no progression over time.
sleeves. Such a presentation makes MR myelography a valuable adjunct in cases where disc or canal pathology is seen to be present on the standard MR images, but where its effect on the nerve root is not clear (Hofman and Wilmink 1996; see also Chaps. 4 and 5).

The MR myelographic dataset shown in Fig. 2.14 were produced with a multi-slice, multi-shot technique requiring a lengthy acquisition 6 min. 30s. A single-shot technique can be employed to reduce acquisition time (Karantanas et al. 2000), and a refinement of this sequence is used in our department. When the echo-train length of an FSE sequence is increased to equal the number of acquired profiles, a strongly T2-weighted myelographic image can be produced with only a single excitation. Such an image possesses a poor signal-to-noise ratio (SNR), however (Fig. 2.15). When multiple, successive, single-shot excitations are now performed to improve the SNR, an MR myelographic image is produced requiring a total acquisition time of only about 30s, with an image quality comparable to a much lengthier multi-slice, multi-shot acquisition (Fig. 2.16).

There are other technical options available to produce MR myelographic images, using gradient-echo T2*weighted sequences (Zisch et al. 1992; Schnarkowski et al. 1993; Eberhardt et al. 1997; Baskaran et al. 2003). These will not be discussed in detail here.

It must be stressed that MR myelography is ancillary to the standard MRI investigation, and can never replace it (Thornton et al. 1999; O’Connell et al. 2003). MR myelography has the same drawbacks as conventional contrast myelography: false negatives occur when the root is compressed distal to the root sleeve, in the foramen or the sacral canal, and false positives are seen when non-filling of a root sleeve is not due to compression (see Chap. 3, Fig. 3.5). The standard MRI cuts and the MR myelographic images should always be carefully matched against each other, and also against the clinical presentation. If a small L5-S1 herniation for instance is seen to be extending into the epidural fat ventral to the dural sac but the root sleeve at the same level is normally depicted and filled with CSF on the MR myelogram (see Fig. 4.3), the clinical signs and symptoms of the patient should be reviewed with extra caution because a chance finding of an asymptomatic herniation is then quite likely.
2.4 Magnetic Resonance Imaging (MRI)
Fig. 2.15 MR myelography. Single-shot, single-slice MR myelographic images in normal spinal canal (a), acquisition time 1.5 s, compared to multi-shot, multi-slice MIP image in same individual (b), acquisition time 6 min. 30 s. Note much poorer signal-to-noise ratio in single-shot image.

Summary

Imaging sequences and features best shown by these in degenerative conditions.

- **T1-W**: Epidural and foraminal fat; lateral and foraminal disc herniations in regions containing fat (foramen, lumbosacral transition and sacral canal). Disc herniations adjacent to dural sac are not well seen; intradural nerve roots are not well seen.

- **T1-W + Gd**: Epidural veins; enhancing annular fissures; inflammatory epidural reaction around an extruded disc fragment, inflamed nerve root, post-operative epidural scarring or spondylodiscitis. Epidural scar or bone marrow enhancement is usually better seen with spectral fat suppression.

- **T2-W**: Dural sac and contents; central and paracentral disc herniations impinging on the dural sac; water content of the nucleus pulposus; fissures in the annulus fibrosus.

- NB: When FSE is used for T2-W imaging, epidural and foraminal fat signal is sufficiently bright to outline disc herniations in foramen, lumbosacral transition and sacral canal.

- Proton density-W: Rupture of outer annulus fibrosus.

- T2++W MR myelography: Cauda equina, root sleeves, normal and compressed.
As a general rule, in sectional imaging, anatomic surfaces or structures are best imaged in a plane which lies perpendicular to the surface of interest, and least well in a plane parallel to this surface. Thus, vertebral endplates are best seen in sagittal and coronal sections, and not well in the axial plane because of partial volume effects. The inner pedicular borders are best seen in axial and coronal sections, and not well in sagittal cuts.

*Sagittal*: Images in this plane are best for demonstrating disc herniations and distinguishing between “contained” protrusions (whose maximum height does not exceed the height of the parent disc) and extrusions, in which the displaced disc material passes through a rupture in the outer annulus fibrosus and extends cranial and/or caudal to the vertebral endplates bordering the disc space (see Chap. 4 and Fig. 4.3). The distinction between diffuse disc bulging and broad-based herniation is often difficult to make in the sagittal plane, and the lateral recesses and the root sleeves are not well imaged. The foraminal borders on the other hand are best defined in sagittal images, as is cranial migration of extruded material in the foramen with compression of the dorsal root ganglion against the pedicle (see Fig. 4.5). The mid-sagittal diameter of the spinal canal is better assessed in the sagittal plane than on axial images, as are spinal deformities such as anterolisthesis and retrolisthesis. Isthmic fractures in spondyloysis may be detected, as well as increase or decrease in sagittal diameter of the spinal canal which is associated
with spondyloytic and degenerative anterolisthesis, respectively (see Chap. 4 and Fig. 4.20).

**Axial:** Images in this plane permit the best classification of the axial location and extent of a disc abnormality, diffuse, broad-based or focal (see Chap. 4 and Fig. 4.2). Migration of extruded disc material cranial or caudal to the level of the endplates can be hard to assess due to partial volume effects. The lateral recesses of the spinal canal are best studied in the axial plane, as well as lateral encroachment upon the spinal canal due to hypertrophy of the facets and flaval ligaments, and the passage of the traversing nerve roots through these regions may be traced. Isthmic fractures in spondylolysis can often be seen in axial images. When measurements of the sagittal diameter of the spinal canal are performed in the axial plane, error due to tilting of the plane of section relative to the longitudinal axis of the spinal canal should be taken into account (see Fig. 2.5). The foramen and its contents can be studied in axial images, but less well than in the sagittal plane.

**Oblique:** Sections can be acquired or reconstructed in the plane of the emerging root sleeve, usually 20–30° off-coronal. Left and right oblique sections are sometimes difficult to position with exact symmetry, and this can make it difficult to compare the course of left and right root sleeves and nerve roots, especially with thin sections. Oblique 3D virtual images of the dural sac acquired in T2-weighted MR myelographic projections do not suffer from this drawback.

**Coronal:** This imaging plane is used only rarely in diagnosis of degenerative disease. Some spinal deformities such as scoliosis or hemivertebra are imaged best in the coronal plane.

### 2.4.7 Upright Imaging

The introduction of open MRI systems has made upright weight-bearing MRI studies possible, with the additional option of dynamic flexion-extension imaging of the spine (Weishaupt and Boxheimer 2003; Jinkins et al. 2005). As discussed in detail in Chapters 3 and 4, the effect of such postural changes on normal and pathologic spinal anatomy makes this a valuable addition to our diagnostic arsenal, most likely to be useful in cases with spinal developmental stenosis or another form of narrowing of the spinal canal.

### 2.4.8 Considerations of Field Strength

Increasing the field strength of the magnet used for MRI produces an equivalent increase in signal-to-noise ratio and hence in low-contrast resolution in the MR image. A study comparing image quality at 0.5, 1 and 1.5T showed image quality at the two higher field strengths to be superior to that obtained at 0.5T (Maubon et al. 1999). If desired, the increase in signal can also be traded off against other image properties: thinner slices or an increase in matrix size to improve spatial resolution, or a larger field of view to expand anatomic coverage without sacrificing image quality. Alternatively, the acquisition time can be reduced.

There are other factors beside field strength affecting image quality in MRI, the most important being the characteristics of the RF antenna or coil employed. In addition, imaging at higher field strengths such as 3T produces increased chemical shift artefacts, susceptibility and flow artefacts and also problems with energy deposition in body tissues. A drawback is the loss of fluid-tissue contrast in T1-W FSE images due to increased T1 relaxation times at higher field strengths. T1-weighted images produced by GRE and fluid-attenuated inversion recovery (FLAIR) sequences suffer less from this problem (Shapiro 2006).

### 2.4.9 Abbreviated Scanning Protocols

The suggestion has been made to reduce the number of acquisition sequences per spinal MRI study, in the interest of increasing patient throughput. In a study comparing a rapid two-sequence screening protocol lasting 2 min. 30s and a detailed four-sequence protocol requiring 28 min, all moderate and severe bulges and herniations were detected by the rapid protocol but more subtle changes were better seen in the detailed examination (Robertson et al. 1996). Another study (Chawalparit et al. 2006) showed disc herniations to be demonstrated equally well by the two imaging protocols, but sensitivity for nerve root compression was significantly poorer in the screening protocol. In a study comparing a rapid MRI examination with spinal radiographs in a group of 380 patients with low back pain (Jarvik et al. 2003), clinical outcomes were the same for both groups but costs were greater in the MRI
group while more patients were operated (10 in the MRI group versus four in the radiography group). Costs of rapid MRI were about half those of a conventional MRI study (Gray et al. 2003).

References


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