Chapter 3

Seeing is Believing: Introduction to Image Contrast

3.1 Introduction

In this chapter you will learn what MR images can show, and get an introduction to the different types of contrast that can be produced. We will use a very simple classification of the body tissues, which will be good enough to describe the basic appearances:

- fluids – **C**erebro**S**pinal **F**luid (CSF), synovial fluid, oedema;
- water-based tissues – muscle, brain, cartilage, kidney;
- fat-based tissues – fat, bone marrow.

Fat-based tissues have some special MR properties, which can cause artefacts. Artefacts are disturbances in the image, which can be misinterpreted as pathology or can hide the real anatomy. Fluids are different from other water-based tissues because they contain very few cells and so have quite distinct appearances on images. (Flowing fluids are rather complicated and their appearance depends on many factors including their speed; they are dealt with in detail in Chapter 15.) Pathological tissues frequently have either oedema or a proliferating blood supply, so their appearance can be due to a mixture of water-based tissues and fluids.

Various tissues have different signal intensities, or brightness, on MR images. The differences are described as the image contrast, and allow us to see the boundaries between tissues. For example, if a tumour is bright and brain tissue is a darker shade of grey, we can detect the extent of the tumour (Figure 3.1a). MRI allows us to produce a wide range of contrasts by using different imaging techniques (known as *pulse sequences*) and by controlling the timing of the components that make up the sequences. So it is also possible to make the tumour dark and brain tissue brighter (Figure 3.1b). Note that this is quite separate from changing the window and level: that can make the whole image darker or brighter, but the tumour will always be darker than the brain tissue. Compare this with CT images. CT contrast depends only on the attenuation of X-rays by the tissues (measured in Hounsfield units). In CT we can produce 'soft tissue' or 'bony' windows by changing the reconstruction algorithm, but bone will always be the brightest tissue and grey matter will always be darker than white matter.

In this chapter we will show:

- the basic labels that are used to describe images: T_1, T_2, proton density and so on;

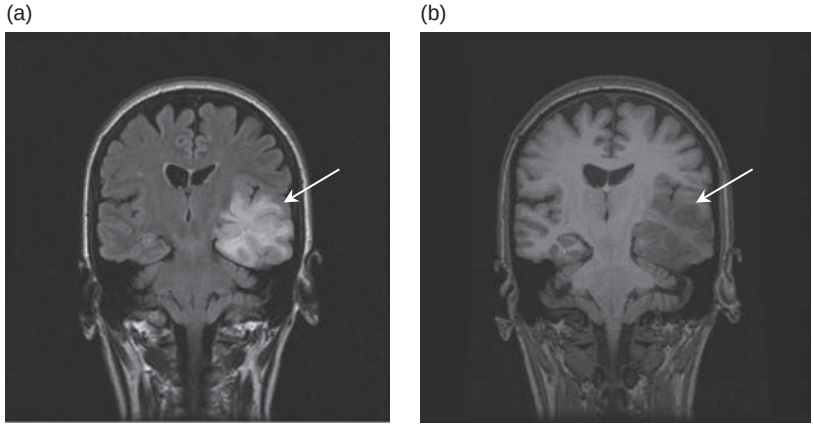

Figure 3.1 (a) Coronal image of the brain showing a tumour (arrow). In this image the tumour is bright against the darker grey of the normal brain tissue. (b) The same slice with a different pulse sequence, this time showing the tumour darker than the surrounding brain.

- we can achieve different contrasts with the basic spin-echo and gradient-echo pulse sequences, by changing the TR and TE times and, in gradient echo, the flip angle;
- STIR and FLAIR sequences are available for suppressing fat or CSF respectively, leaving a 'T_2-weighted' appearance in the remaining tissues;
- injected contrast agents can improve image contrast by enhancing signal intensity in tumours;
- there are two special scans, MR angiography and MR diffusion imaging, which are important in many basic exams, and they will be explained here.

Clinical Exam 1: Simple Brain

All MR exams consist of a survey followed by at least two more scans with different image contrasts. Many exams contain four or more scans; each new contrast provides different information about the anatomy and pathology, and helps to improve diagnostic confidence in the result.

A very simple brain exam might contain a T_2w image and a FLAIR, with T_1w images pre- and post-Gd. (Here, 'Gd' is shorthand for an injected contrast agent containing gadolinium, Gd. More about that later.) The T_2w and FLAIR images are both sensitive to fluid collections; the FLAIR images show CSF as a black signal, which helps to distinguish periventricular lesions. T_1w images have better contrast between **G**ray **M**atter (GM) and **W**hite **M**atter (WM), which helps to show mass effect or effacement of GM/WM boundaries. The Gd contrast agent leaks into the brain tissue wherever the blood–brain barrier is impaired, and gives a bright enhancing signal on T_1w images after injection. This gives further delineation between pathological tissue and oedema.

In Figure 3.3, both images are shown in the transverse plane, so you can easily see how the different contrasts affect the appearance of the normal anatomy and pathology. However, radiologists can get even more information by acquiring the images in different planes, e.g. coronal or sagittal, and mentally building a 3D overview of the patient's condition while reading the images.

3.2 Introduction to the T-Words

All these strange acronyms beginning with 'T' – what language is this? Like any other field of medicine (or science), MRI has its own jargon which can be confusing at first. Table 3.1 introduces you to the main words, with a short description. We won't explain all the detail yet, because it can be overwhelming. For now, just use these terms as labels.

Table 3.1 Overview of important MRI terms

Term	Description
T_1	A property of a tissue, called *spin–lattice relaxation time*
T_2	A property of a tissue, called *spin–spin relaxation time*
T_2^*	A property of a tissue in a magnetic field, called *apparent spin–spin relaxation time*
PD	A property of a tissue, called *proton density* (closely related to *water content*)
TR	A timing parameter for a scan, called *repetition time*
TE	A timing parameter for a scan, called *echo time*
TI	A timing parameter for a scan, called *inversion time*
α	A parameter for a scan, called *flip angle*
T_1w	Description of image contrast, dependent mainly on T_1 of tissues
T_2w	Description of image contrast, dependent mainly on T_2 of tissues
T_2^*w	Description of image contrast, dependent mainly on T_2^* of tissues
PDw	Description of image contrast, dependent mainly on PD of tissues

3.3 T_2-Weighted Images

T_2-weighted (T_2w) images are one of the most important MR images, because they are sensitive to fluid collections. Since many pathological tissues have high capillary density, or excess fluid accumulations, these images provide confirmation of the preliminary diagnosis and show the extent of the disease. So, for example, the meniscal tear in the knee shows up well because the synovial fluid in the tear is brighter than the cartilage (Figure 3.2). T_2w contrast can be produced by either **S**pin-**E**cho (SE) or some **G**radient-**E**cho (GE) sequences. (GE sequences actually produce T_2^*-weighting, not T_2-weighting: the image appearance is similar, but there are important differences which we will explain later.) SE T_2 images require long TR and long TE, so they have a long scan time (this is because the scan time depends directly on the TR).

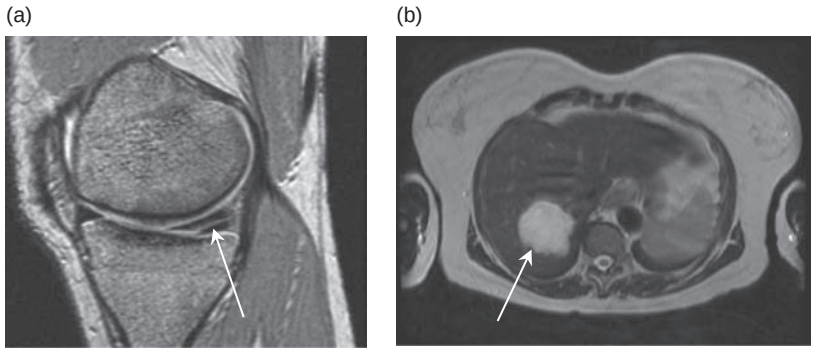

Figure 3.2 T_2-weighted pathology images. (a) Sagittal image of meniscal tear (arrow) and (b) axial liver scan showing haemangioma.

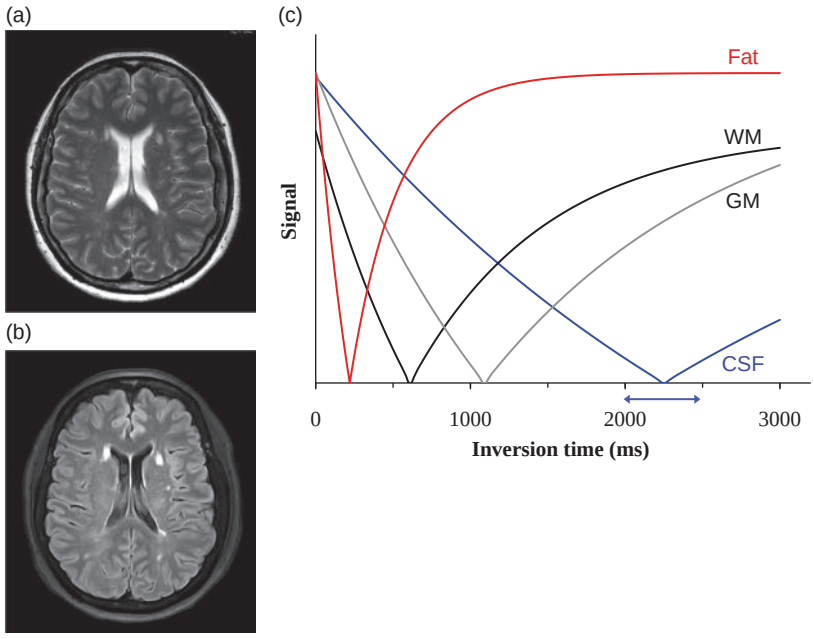

Figure 3.3 (a) SE T_2w and (b) FLAIR images in a patient with multiple sclerosis (MS). Notice that the lesions are better seen when the CSF signal is suppressed. (c) Inversion recovery curves showing the range of null point for CSF.

On T_2w images tissues with long T_2 relaxation times are brighter than those with short T_2s. For brain and spine imaging, T_2w images are usually acquired with the spin-echo pulse sequence. For liver, where a breath-hold is needed, the T_2w images can be acquired using gradient echo which is faster – but remember that this is actually T_2^*w, not T_2w (see Section 3.9 for more information).

3.4 FLAIR Images

The very high signal of CSF in brain T_2w images can give problems for the radiologist to identify periventricular lesions. It is possible to remove the CSF signal, known as 'nulling the signal', by choosing an **I**nversion **R**ecovery (IR) sequence instead of spin echo, and carefully setting the inversion time (TI). This combination of IR with a certain TI to null CSF is known as FLAIR (**FL**uid **A**ttenuated **I**nversion **R**ecovery (Figure 3.3a,b)). Because of the long spin–lattice relaxation time T_1 of CSF, there is a wide range of TIs which will give reasonably good fluid suppression, typically between 1800 and 2500 ms depending on the magnet's field strength (Figure 3.3c). Be aware that all tissues with T_1s similar to CSF will be suppressed, and FLAIR is not recommended after gadolinium injection because of the variable effects on T_1s.

3.5 T_1-Weighted Images

T_1-weighted (T_1w) images can be produced using either SE or GE sequences. Unlike T_2w images, where

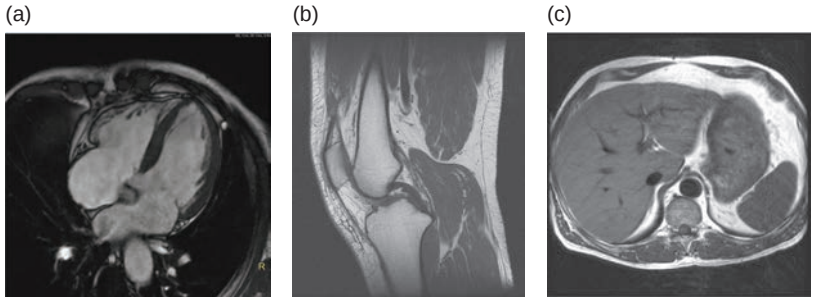

Figure 3.4 T_1-weighted images of normal anatomy. (a) Oblique 'four-chamber' view of the heart, (b) sagittal knee, (c) axial liver.

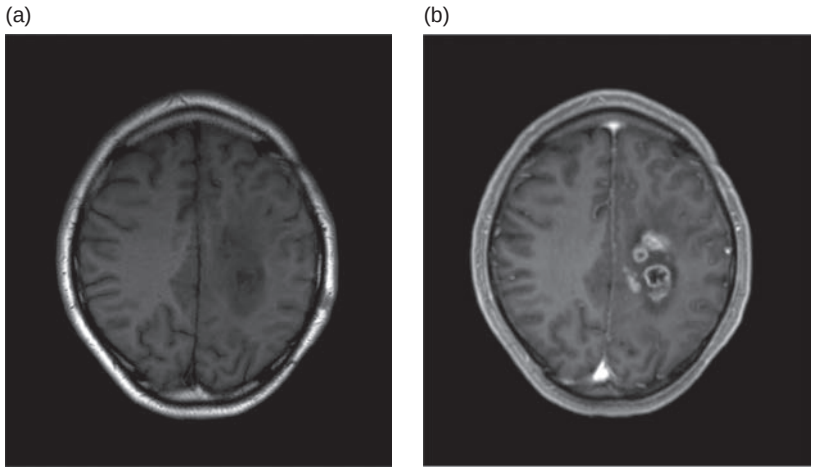

Figure 3.5 (a) Pre-Gd and (b) post-Gd SE T_1 images of a high-grade glioma.

long T_2 tissues have a bright signal, on T_1w images the longest T_1s have the darkest signal. Tissues with short T_1s appear brighter. T_1w images are usually quite fast to acquire, because they have short repetition times (TR). T_1w images often have excellent contrast: static fluids, e.g. synovial fluid, are very dark, water-based tissues are mid-grey and fat-based tissues are very bright. The appearance of flowing fluids (e.g. blood) depends on the speed of flow and the sequence parameters. T_1w images are often known as 'anatomy scans', as they show most clearly the boundaries between different tissues (Figure 3.4).

3.6 T_1w Images Post-Gd

Although MRI is extremely flexible in creating different image contrasts, just by manipulating the pulse sequence and timing parameters, there is still a role for injected contrast agents. The most commonly used contrast agents are based on gadolinium (**Gd**), a metallic element with a strong paramagnetic *susceptibility* (refer back to Section 2.4.2 for definition of different magnetic properties). When a Gd contrast agent is injected into the body, it starts in the veins and arteries but rapidly leaves the blood vessels into the extracellular fluid spaces (with a half-life of around 10 min), and is then gradually excreted via the kidneys. The total body dose has a half-life of around 90 min in subjects with normal kidneys, and can be considered completely eliminated after 24 h. It has the effect of shortening the T_1 of tissues where it accumulates, so the most useful images to acquire post-Gd are T_1-weighted. We normally keep exactly the same parameters for the scan pre- and post-Gd, so that comparison between the images is easier. It's especially important to keep the same window/level on the two scans – although it can be very difficult to do this!

Since Gd reduces the T_1s, the affected tissues will have higher signals on the post-Gd T_1w images. For example, highly vascular tumours will become brighter and where the blood–brain barrier is disrupted gadolinium will leak into the region and enhance that area (Figure 3.5).

Technical Interlude for the Curious

We have already introduced several new concepts which deserve some extra explanation. This box will give you some basic info to help you through the next sections.

MR images are produced using a repeating series of RF and gradient pulses, known as a *pulse sequence* or simply *sequence*. All sequences have a *repetition time TR*, and an *echo time TE*, which control the sequence timing. All sequences have an *excitation* RF pulse which disturbs the body's protons and creates a signal in the RF coils. The signal can be detected by forming either a *spin echo (SE)* or a *gradient echo (GE)*. SE sequences have a second RF pulse for *refocusing* the signal echo, and this extra pulse corrects the signal for B_0 inhomogeneities. GE sequences use gradient pulses to create the echo, which can be much faster than SE, but has sensitivity to B_0 inhomogeneity. A useful variant of SE is the *inversion recovery (IR)* sequence, which starts with a 180° pulse to invert the protons' magnetization. The delay between the inversion pulse and the excitation pulse is called the *inversion time (TI)*. By setting TI to a particular fraction of the T_1 of a tissue it is possible to *null* the signals from that tissue. The important fraction is $0.693 \times T_1$.

T_1 and T_2 are fundamental properties of all tissues. They describe the two kinds of *relaxation* which allow the protons to get back to their equilibrium condition. T_1 is known as *spin–lattice* or *longitudinal* relaxation time and is always longer than T_2. T_2 is known as *spin–spin* or *transverse* relaxation time. Through many experiments in the last 30 years, we have good knowledge of the T_1 and T_2 times for body tissues.

Clinical Exam 2: Spine

The spine may be examined either for neurological problems, or for **M**usculo**SK**eletal (MSK) indications. Sagittal scans are the most important because they show the whole area within one set of images. Spine exams always include T_1w and T_2w scans in the sagittal plane. We will then acquire a stack of T_2w images in an oblique transverse plane through areas of particular interest, for example a prolapsed disk.

For neuro indications, it's important for the transverse T_2w images to show the internal anatomy of the spinal cord, and GE T_2^*w is usually best for this. For MSK, it's usually more important to be able to trace the nerve roots as they exit the spinal canal, and SE T_2w is often better for this.

A third type of contrast, called STIR, is often used in the sagittal plane. STIR stands for *Short TI Inversion Recovery,* so it is another IR sequence like FLAIR. However, in this case the TI is chosen to null fat signals, which have much shorter T_1s than CSF. Using short TI, fluids with long T_1s give a high signal, so the STIR appearance is approximately 'T_2w with fat suppression'.

Spine imaging in modern wide-bore scanners is very simple for patients. The receive RF coil lies underneath the patient couch, and a shaped head–neck coil offers support for the cervical spine. The majority of spine exams are performed with the patient head-first into the scanner. However it is possible to do lumbar spine exams with the patient feet-first, a configuration which can help some claustrophobic patients to feel more comfortable.

3.7 STIR Images

You will often hear people ask for STIR (**S**hort **TI** **I**nversion **R**ecovery) images, especially for spine and for musculoskeletal imaging (Figure 3.6). STIR images have very low signal from fat but still have high signal from fluids, i.e. they can be thought of as a 'fat-suppressed T_2w' imaging technique. However, bear in mind that STIR images will suppress all tissues with the same T_1 as fat, so they should not be used after gadolinium contrast injection when there may be T_1 changes in the pathology as well as in normal tissues.

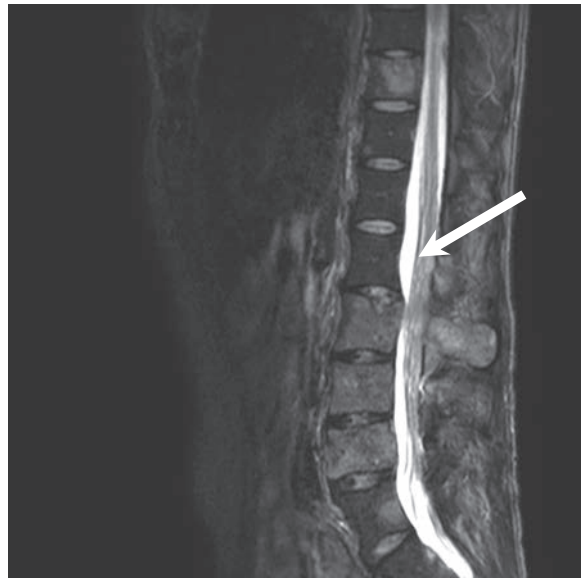

Figure 3.6 STIR image of bone marrow changes in spine.

STIR is a type of IR sequence, like FLAIR, except that we choose to null fat-containing tissues instead of CSF. The appropriate TI depends on the T_1 of the tissue and should be about 70% of the T_1. For example, fat has a T_1 of 220 ms at 1.5 T, so if we set TI to 150 ms, the signal from fat can be suppressed. You may need to adjust the TI slightly either side of this value to achieve the best fat suppression, since TE and TR also have an impact on nulling the signal. At other field strengths TI will be different, e.g. fat T_1 is approximately 380 ms at 3.0 T, so STIR sequences require a TI of around 260 ms.

There are other methods for removing or reducing the signal from fat, and STIR is not always the best choice. See Section 7.3.3 for a more detailed explanation and evaluation of the strengths and weaknesses of fat suppression techniques.

Clinical Exam 3: Knee or Shoulder

After brain and spine exams, musculoskeletal (MSK) referrals are the most common in many MR centres. Since the size and location of the main joints are very different, there are often dedicated RF receive coils for each area. However, the sequence choices are fairly similar, since we are typically looking for detailed information about the joint structures.

STIR is sometimes used in larger joints to achieve a fat-suppressed T_2w appearance. Proton-density-weighted (PDw) imaging is very useful in knee and shoulder, especially when using an alternative method to suppress fat. T_1w images may be used pre- and post-Gd if there is a history of surgery.

Many patients have joint replacements, and these often contain large amounts of metal. You should always carefully check the type of implant, to see if it is safe to scan. If it is safe, you may find that the large amounts of metal create strong artefacts in the images. There are new imaging sequences available on some scanners to minimize this effect: see Chapter 7 for details.

Positioning patients for MSK exams is a question of personal preference and RF receive coils available. Shoulders, hips, knees and ankles are straightforward, using a supine position. Elbows and wrists, however, are tricky in conventional 60 cm-bore systems. Often the 'superman' position is needed, with the patient lying semi-prone with the affected arm stretched above their head, in order to get the coil into a good position. It is difficult for many patients to hold this position, which may limit the exam time to around 20 min. In wide-bore systems these joints can be imaged with the patient lying supine with the arm by their side, often with enough space to move their body slightly off-centre and allow the elbow/wrist coil to be more central in the scanner.

Technical Details: SE Sequence

As we have seen, it is possible for SE sequences to produce images with T_1w, T_2w or PDw, just by changing the timing parameters. Suppose you need to change one of these parameters during an exam, for example to keep scan time low. How do you make sure the timing will still produce the required contrast? You need to learn some technical details about the SE sequence and practise using it.

In some ways the SE sequence is simple to understand: it has just two RF pulses, one for excitation and one to refocus the echo. The repetition time TR is the time between two consecutive excitation pulses, and TE is the time between excitation and the signal echo. In its simplest form, the TE is twice the time between the excitation and refocusing pulse.

We can image the brain using a fixed (long) TR, and vary the TE from 10 ms to 100 ms. The series of images is shown in Figure 3.7a. If we measure the signal of GM, WM and CSF on each of these images, we can plot the signals against TE on a graph (Figure 3.7b). Notice that the longer TEs have the maximum contrast – the most difference between signals – even though they have lower **S**ignal-to-**N**oise **R**atio (SNR) overall. These are the T_2w images which are so common in MRI.

Next we can image the same brain with a fixed (short) TE, and vary the TR from 50 ms to 1000 ms. This series of images is shown in Figure 3.8a and the corresponding signal curves are shown in Figure 3.8b. This time we see that the maximum contrast occurs at shorter TRs, although again the overall SNR is low. These are the T_1w images.

If we want to acquire PDw images, we need to minimize the effects of both T_1 and T_2. That means we should use the longest possible TR and shortest TE. These images will have high SNR, as you can see from the curves in Figure 3.7 and Figure 3.8.

Suppose we go a bit crazy, and image the brain with short TR and long TE – what does an image look like with both T_1 and T_2 weighting? See Figure 3.9 for an example. It has extremely low SNR, and we now cannot be sure what a high signal intensity means: is it a short-T_1 tissue, or a long-T_2 tissue? This is not helpful for the radiologist, so make sure you don't do it!

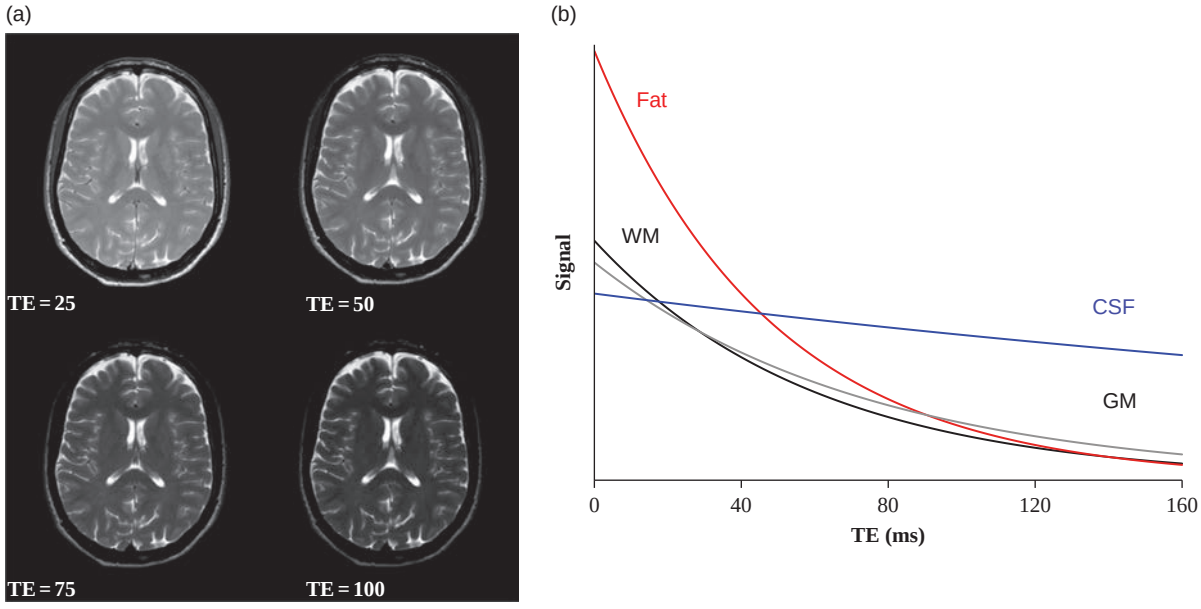

Figure 3.7 (a) SE brain images with TR = 1500 ms and various TE. (b) Signal intensity for brain tissues plotted against TE.

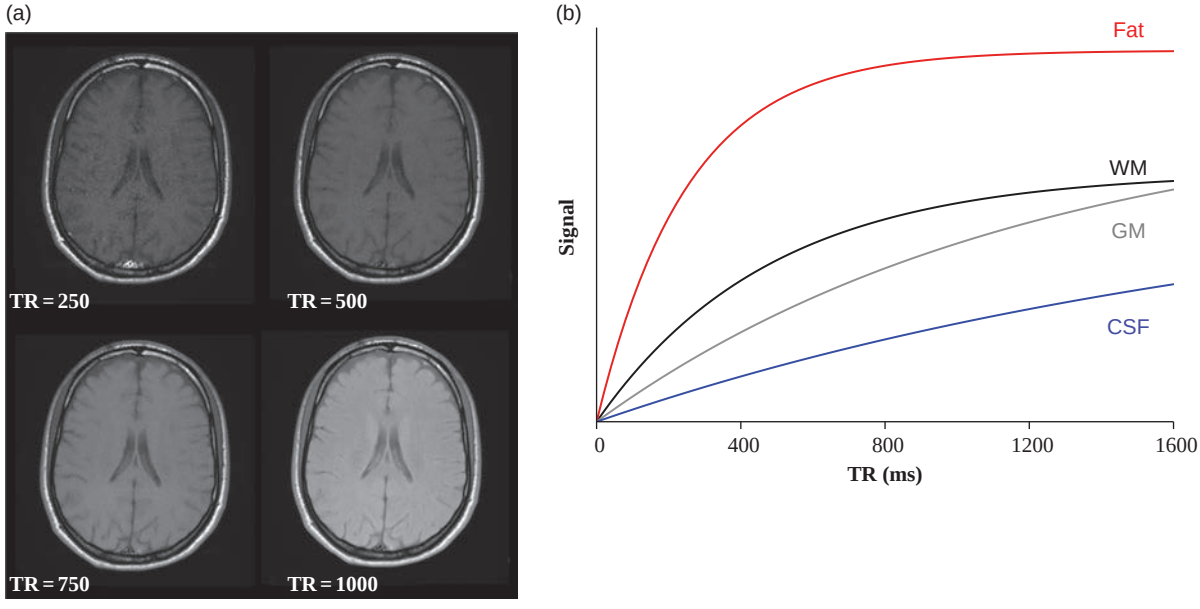

Figure 3.8 (a) SE brain images with TE = 10 ms and various TR. (b) Signal intensity of CSF, grey and white matter, and subcutaneous fat plotted against TR.

3.8 PD-Weighted Images

We have already introduced two fundamental properties of tissues in the body: T_1 and T_2 relaxation, which are used to create contrast in MR imaging. The third important property is the proton density, PD. Proton density is essentially the water content of the tissues, and so it does not vary much, ranging from 75% to 85% in most organs. Although this limited

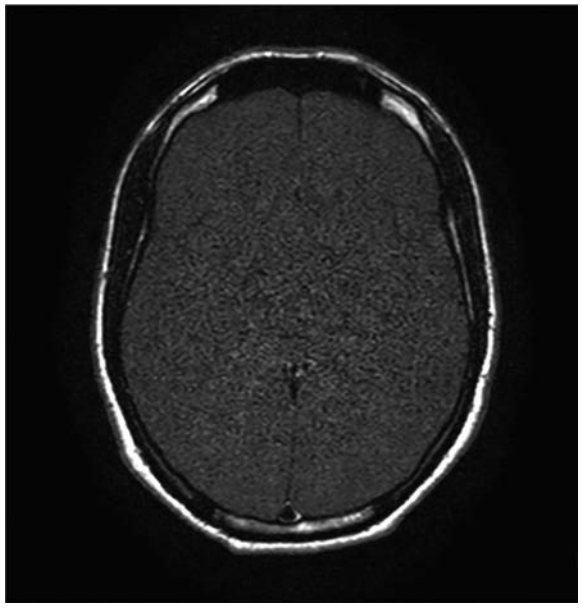

Figure 3.9 Image of the brain acquired with short TR (150 ms) and long TE (80 ms).

Figure 3.10 Sagittal PD-weighted image of the knee.

range means that PD scans are rather 'grey', i.e. lack contrast, compared with T_1w or T_2w scans, they have some useful clinical applications; for example, in the knee you can distinguish articular cartilage from the cortical bone and menisci (Figure 3.10). PDw images can be produced either with SE or GE sequences; however, for musculoskeletal imaging it is usual to stick to SE.

Try It for Yourself 1: Contrast on Spin-Echo Images

One of the best learning experiences is to produce MR images yourself with different timings to see the effect on contrast. For ethical reasons it is better to use a phantom than to scan one of your friends; fill leak-proof bottles with cooking oil (representing fat signals) and water. If you can find an out-of-date bottle of gadolinium contrast, use it to change the T_1 and T_2 of more bottles of water; you only need 0.1–0.2 ml per litre of water. Arrange the bottles within the head coil or knee coil, do a localizer scan and then start playing. Make sure you only change one parameter at a time, keeping all the others constant.

A few hints (some scanners have little tricks which can catch you out):

- Don't use fast spin echo (turbo spin echo), use the conventional spin echo without an echo train.
- Short TRs or long TEs don't allow many slices: check how many you can get before you set up the long TRs and short TEs. You need to scan slices at exactly the same locations to get a proper comparison of contrast.
- Don't be stingy with the slice width, you're not looking for high resolution here. Go for 10 mm.
- Make sure you keep the same receiver gains for all the scans. Check your manufacturer's system manual to see how to do this. This will allow you to measure the signal intensity within regions on the images, and then plot curves similar to the ones in this chapter.

Technical Details: IR Sequence

We already mentioned that the IR sequence is a variant of SE, with an extra *inversion* RF pulse at the start. As the name suggests, this first pulse tips all the protons upside-down. From this position, they return back towards equilibrium via T_1 relaxation. When the excitation pulse is applied, some of the protons may still be in the negative direction, some will be positive (almost back to equilibrium) and some may be at exactly zero. Their position depends on the T_1 of the tissues. Tissues which are at zero will not give any signal in the imaging sequence; they are said to be nulled.

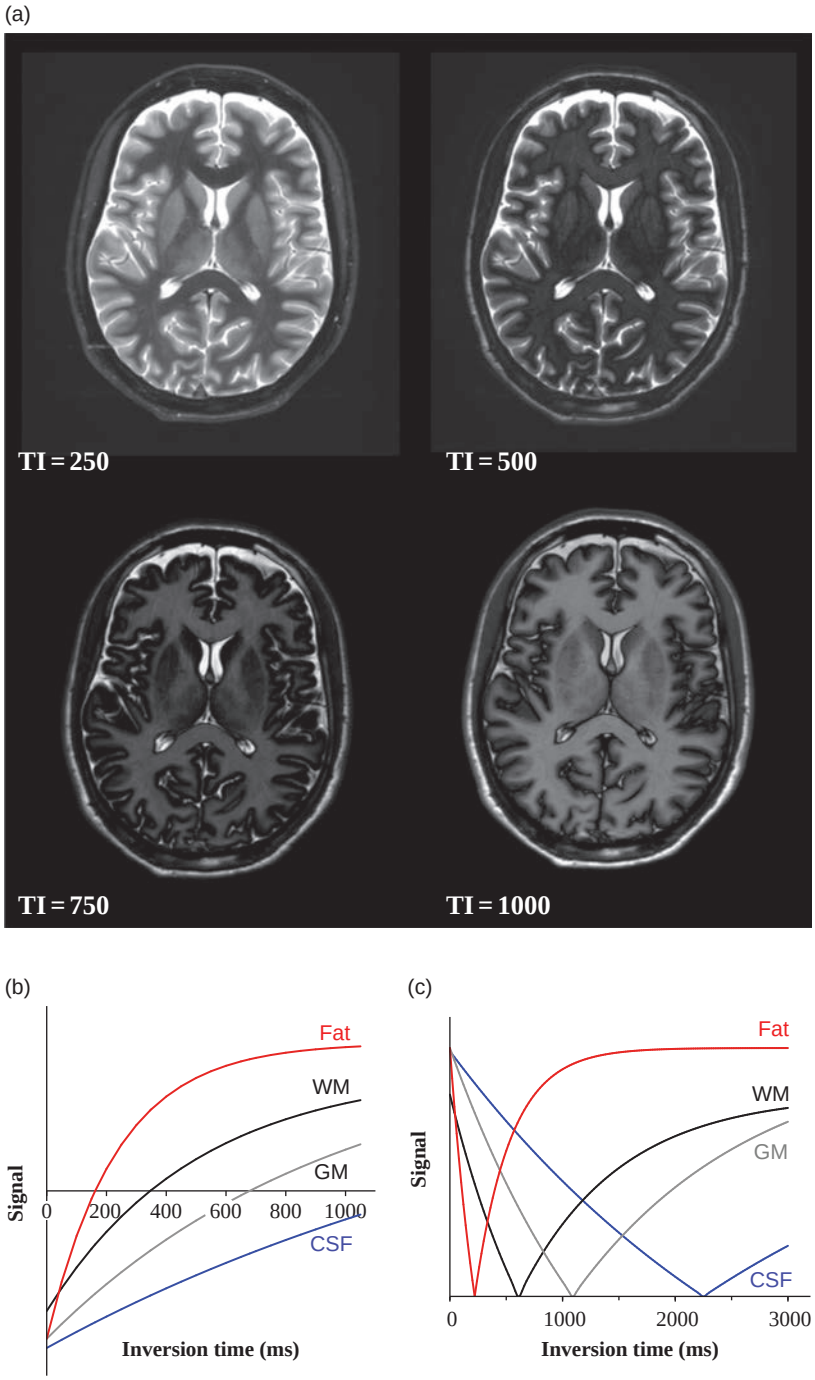

Figure 3.11 (a) Inversion recovery images at various TI with TR = 8000 ms and TE = 10 ms. (b) Signal curves plotted from these images. The curve for fat indicates the appropriate TI for a STIR image. (c) Inversion recovery curves showing magnitude signals (as most commonly used in scanners) with only positive values.

Using the brain example again, the sequence of images in Figure 3.11a shows a fixed TR of 8000 ms, a fixed TE of 10 ms and TI varying from 100 ms to 3000 ms. By plotting the signal values against TI (Figure 3.11b), you can see how tissues change from negative to positive, and by selecting the right TI we can make a fat-suppressed image (STIR) or a CSF-suppressed image (FLAIR).

Normally MR images don't show negative and positive signals; they are simple *magnitude* images where the signal brightness only shows the size of the MR signal, not its direction (whether it is positive or negative). If we re-plot the same image series using magnitude signals only, the curves show a characteristic dip to zero before rising back up again (Figure 3.11c).

3.9 Gradient-Echo Images

The gradient-echo (GE) sequence is extremely versatile, allowing for T_1w, T_2^*w and PDw images. For the beginner, the first problem is that there are lots of different GE sequences with different names – how do you know which one to choose? There are important differences between these sequences, so we will eventually have to explain which is which (see Chapter 13). In this chapter, we will simply tell you the appropriate sequence for the main manufacturers.

Although the sequence choice is important, the choice of excitation *flip angle*, α, is much more important to determine the contrast in the images. GE sequences generally use small flip angles for excitation, often less than 90°, which is normally used in SE sequences. They also have very short TRs compared with SE, between 15 ms and 250 ms. Looking back at Figure 3.8b, we would expect to have very little SNR (**S**ignal-to-**N**oise **R**atio) with such short repetition times. However, by reducing the excitation flip angle to e.g. 30°, we can avoid this signal loss. A 30° excitation RF pulse leaves most of the protons in their equilibrium position, aligned with the main magnetic field. This means that full relaxation can be achieved in a very short time (typically less than 500 ms). So even with a short TR, using α = 30° will avoid T_1w in the images, leaving either PD or T_2^*w (depending on the chosen echo time).

Alternatively, using α = 50° or higher affects more of the protons, leaving fewer in the equilibrium position, and we can create more T_1 weighting. (The exact choice of α depends on which GE sequence you are using; please read Chapter 13 to understand this complex subject.) You can see the effect of changing α on the signal intensities of brain tissues in Figure 3.12. Notice that intermediate values of α give contrast that is not good for either T_1 or PD.

In daily practice, GE scans give us flexibility to increase the TR to allow extra slices, or reduce it to save scan time. When we do this, we have to maintain the T_1w contrast by adjusting the flip angle to match the TR.

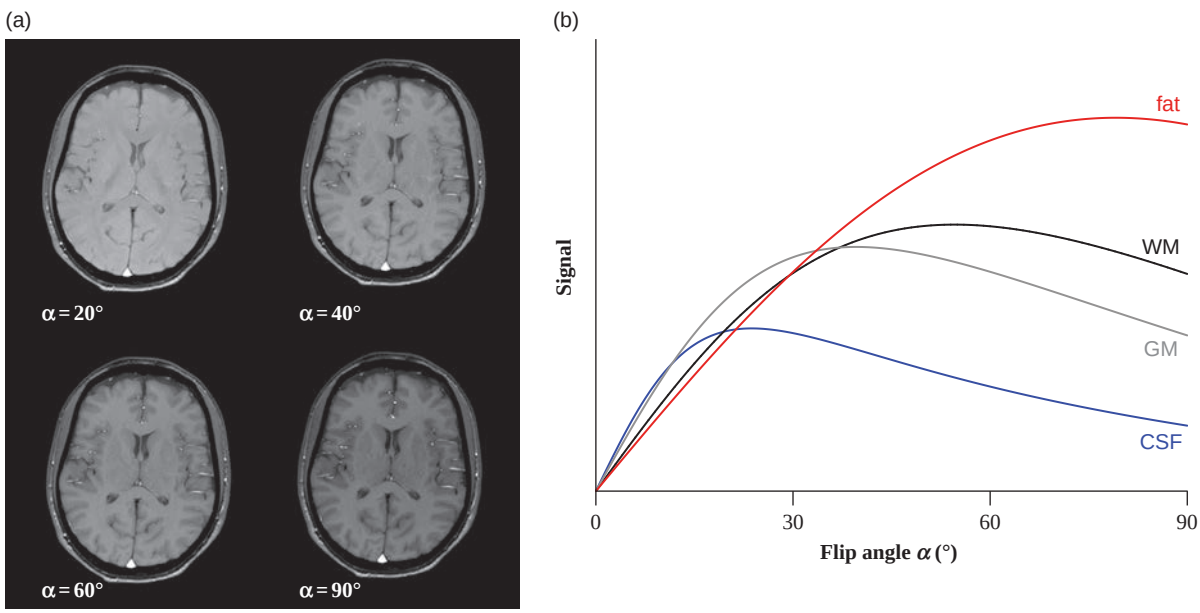

Figure 3.12 (a) GE images with fixed TR (150 ms) and TE (4.6 ms) and various flip angles *α*. (b) Signal intensity of brain tissues plotted against *α*.

3.9.1 Gradient-Echo T_1-Weighted Images

Using the information in the previous section, you can already suggest the timing parameters needed to get T_1w GE images. A short echo time, a flip angle of at least 50°, and a TR of . . . well, it doesn't matter does it? You can set the TR as short as you like, to achieve a very short scan time – but be careful that you don't make it so short that you have no SNR left! See Chapter 6 for more practical hints about optimizing contrast etc. We promised to tell you which GE sequence to select. On GE Healthcare systems, choose SPGR; on Philips, choose T1-FFE; and on Siemens, choose FLASH (see Table 4.2). By the way, throughout this book we shorten gradient echo to GE, and refer to the manufacturer as GE Healthcare.

One interesting variant with T_1w GE images is the possibility to acquire *in-phase* and *out-of-phase* images. This refers to the choice of echo times, which determines whether water and fat signals are either in phase with each other, or out of phase. **I**n-**P**hase (IP) means that both sets of protons are in the same direction, while out-of-phase means that they point in opposite directions. **O**ut-of-**P**hase (OP) images have a characteristic dark line which seems to outline the organs, just like a child's drawing with a black outline. This is due to the interface between the water-based organs and the intra-abdominal fat, giving OP signals for the water and fat in these voxels. This technique allows a radiologist to detect if there is diffuse fatty infiltration in the liver or other organs, since the OP images will show a darker signal than the IP images.

Clinical Exam 4: Liver

Liver MR imaging is becoming more and more common, and it introduces some new challenges for the radiographer. Most scans are done with breath-holding, to avoid motion artefacts as the liver moves with respiration. This means that all scan times have to be reduced to less than 25 s, and preferably closer to 15 s. Spin-echo sequences are too slow for this, so gradient echo is frequently used for liver imaging. Breath-holding in inspiration is easier for the patient and can be held for longer, but expiration breath-holds offer more consistent liver positioning between scans, so expiration is usually the preferred method.

A typical examination would include T_2^*w images, T_1w images acquired in- and out-of-phase, a fat-suppressed T_1w 3D image, and a dynamic series of T_1w scans acquired before and after an injection of Gd. Focal liver lesions react to Gd in different ways, and it is important to see both the uptake and washout of the contrast agent in order to characterize the lesions. Images are mostly acquired in the transverse plane, or the coronal plane.

Positioning patients for liver MRI takes longer than spine or MSK imaging. Before you even get the patient into the scanner room, coach them with the breath-holding instructions, as expiration breath-holding may be new for them. A respiratory belt or device may be necessary for any non-breath-hold scans, and this should be positioned according to the manufacturer's instructions. Liver imaging requires an RF receive coil to be placed over the patient's body. The patient lies supine and can be entered into the scanner either head-first or feet-first. Finally, make sure that the patient can hear you clearly when you talk through the intercom, so that they can follow the breath-holding instructions.

3.9.2 Gradient-Echo T_2^*-Weighted Images

Looking back at Section 3.3, you may have noticed the strange notation (*) next to the T_2w. This is linked to the fact that GE sequences cannot correct for the effects of magnetic field non-uniformities. A perfectly uniform magnetic field simply can't be produced, and even if it could the patient would make it imperfect due to *susceptibility* effects (see Box 'Good Metal, Bad Metal' in Chapter 2). Susceptibility is a term used for low-level magnetic field variations, introduced by anatomy such as sinuses or intestines containing air, or dense cortical bone, or iron-rich blood breakdown products.

These inhomogeneities affect the relaxation of tissues after an RF pulse, making the spin–spin relaxation time appear shorter. We call this the *apparent spin–spin relaxation time* T_2^*, or simply *apparent* T_2^*. It turns out that the effect of the B_0 non-uniformity can be separated from the fundamental T_2 of the tissues, and Chapter 9 will provide much more information about these relaxation processes. For now, it is enough to remember that T_2^* is always shorter than T_2.

If we consider a range of tissue T_2s all in the same imperfect magnetic field then we can say that the tissue T_2^*s will stay in the same relationship to each other. So CSF with T_2 longer than grey matter will also have a T_2^* longer than the T_2^* of GM. The basic contrast in GE T_2^*w images is therefore the same as in

SE T_2w scans (fluids are bright, other tissues are mid-grey). As usual, we tend to be a bit lazy when describing the image contrast, so you might hear the phrase 'gradient echo T_2s'. This is accepted as MRI jargon, because the image contrast is very similar to that of spin-echo T_2s. But do keep in mind that magnetic field non-uniformities will have an effect on all the signals; the scans are actually 'gradient echo T_2^*s'.

To produce GE T_2^* images, select GRE sequences on GE Healthcare systems; choose T2-FFE on Philips; and FISP on Siemens scanners. You need to keep α small to avoid T_1 weighting, and TR can be short for rapid scanning or long enough for multiple slices. The TE is increased to achieve T_2^* weighting, although the TE is always short compared with the TEs used in spin-echo sequences.

By now you can probably work out for yourself how to get a gradient echo PD image. You need to use the same type of sequence as you did for a GE T_1w image, setting the TR to be as short as possible (for a 3D scan) or long enough to get the required number of slices. Since we don't want any T_2 decay, the echo time must be short, and α must be small to avoid creating T_1 contrast. GE PDw images are not often used in clinical practice, so we won't spend any more time on them.

Try It for Yourself 2: Contrast on Gradient-Echo Images

Using your oil and water bottles again, try changing TR, TE and α to see the effect on contrast. You need to use different GE sequences to show T_1 or T_2^* contrast: refer back to the last two sections. As before, there are pitfalls to avoid:

- Short TRs and long TEs don't allow many slices: check first how many you can get.
- Keep all the other scanning parameters the same.
- Keep the same receiver gains for all the scans within a set (e.g. for several different TEs). Measure the signal intensity within regions on the images, and then plot curves.

3.10 More About Contrast Agents

You have already been introduced to gadolinium-based contrast agents in Section 2.5. Gadolinium is very common in MR exams, and there are several different preparations available in the market. There are variations in concentration and dosage, so be sure to familiarize yourself with the manufacturer's information sheet at your institution.

Gd contrast agents are rapidly passed from the arterial system into the extravascular space. From there, they are excreted to the veins and eventually filtered out in the kidneys. In tissues with abnormal vascularity, Gd tends to pool in the extravascular space. The exception to this principle is in the brain, where Gd remains intravascular *except* where the blood–brain barrier is disrupted.

Since gadolinium is paramagnetic, it alters the local magnetic field in areas where it accumulates. Not enough to be measurable, but enough to affect the relaxation times of the tissues. In particular, the tissue T_1 is reduced, and this leads to *higher* signal on T_1w images after Gd injection.

Other paramagnetic metals have been developed as MRI contrast agents. For a while, **S**uper-**P**aramagnetic **I**ron **O**xide, known as SPIO contrast agents, were available for liver MRI. The effect of a SPIO agent is to *reduce* the T_2 of tissues in which it accumulates, causing lower signal intensities on T_2w or T_2^*w images post-contrast. Since SPIO agents are taken up by healthy Kupffer cells, the signal of normal tissue is reduced, leaving pathological tissues with a relative signal enhancement post-injection. However, many SPIO formulations have been discontinued due to disappointing sales in many countries. The only agent left in the market is Lumirem® (Guerbet), available in some European countries and marketed as a rectal or oral agent to delineate the bowel lumen. Manganese is another paramagnetic metal which has been developed as an MR contrast agent. It behaves in a similar way to Gd agents, by reducing the T_1 of tissues where it accumulates. However, like the SPIO agents, sales were poor compared with Gd and there are currently no approved formulations in the market.

Why Doesn't Gadolinium Affect T_2?

The real answer is that gadolinium *does* affect T_2 as well as T_1. The precise effect of contrast agents depends on their concentration in the tissue concerned, and also on the imaging sequence being used. Remember that although images are described as T_1w, T_2w, etc., the signals have contributions from all the magnetic properties of the tissues concerned – T_1, T_2, PD, susceptibility, and so on. At very high concentrations and in sequences with longer TEs, gadolinium may actually reduce the signal intensity of the tissue due to shortening of T_2.

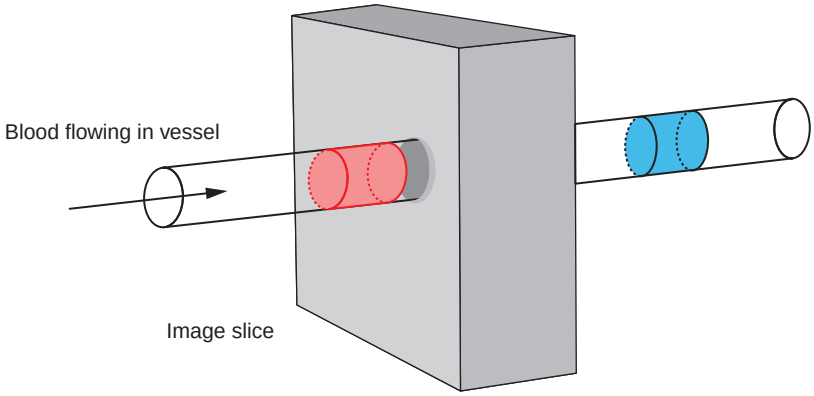

Figure 3.13 The time-of-flight or in-flow effect. The blood vessel is shown crossing through the imaging slice. When the sequence is repeated, the previously excited blood (coloured blue) has moved on and the bolus within the slice (coloured red) has fully relaxed magnetization M_0.

Clinical Exam 5: Advanced Brain

Some neurological conditions are linked with the neurovascular system, so angiography is an important technique in MR. For example, MRI is used in the diagnosis of **A**rterio-**V**enous **M**alformations (AVMs), to monitor aneurysms, and to investigate acute stroke in some specialist centres. **MR A**ngiography (MRA) sequences are mainly based on gradient echo, and may include imaging during an injection of Gd contrast agent. MRA is capable of detecting small aneurysms and vascular stenosis, and can also be sensitive to thrombosis. When high resolution is needed, MRA scans can be quite long (5–6 min).

In many neuropathologies, we use a scan called **D**iffusion-**W**eighted **I**maging (DWI). This scan is sensitive to the tiniest movements of water protons, rather than the bulk flow properties seen in the vascular system. DWI is particularly used in the characterization of focal brain lesions, and can also be used to determine the age of a stroke infarct. DWI is typically a very fast scan, less than a minute, but it is also one of the noisiest scans because it uses very strong gradient pulses to create the diffusion sensitivity. Patients may be alarmed by the noise and may also feel the scanner vibrating during the DWI.

3.11 Angiographic Images

When we were describing T_1w imaging, we mentioned that flowing fluids, such as blood, do not behave like other static fluids, like synovial fluid. You may have noticed that the signal within vessels is very high on GE images and can also cause artefacts. How can a long-T_1 fluid give a high signal on T_1-weighted images? It is because the blood is flowing.

Consider a blood vessel passing through the imaging slice (Figure 3.13). During the repetition time of the sequence, the little plug or 'bolus' of blood within the slice flows out of the slice and is replaced by a new bolus. This blood has not been tipped by the RF pulse, so when the next pulse is applied the blood has its full equilibrium signal. Thus, it will give a high signal even though TR is short and the T_1 of blood is long. This process repeats itself during each TR, so each bolus of flowing blood always gives a high signal. This is known as the 'in-flow' or 'time-of-flight' effect.

We can exploit the high signal of flowing blood in **MR A**ngiography (MRA) using a variety of techniques to suppress almost all the signal in static tissues. The three most important sequences are 'time-of-flight MRA' (also known as 'in-flow MRA'), 'phase-contrast MRA', and 'contrast-enhanced MRA', which uses a very rapid imaging sequence during the injection of gadolinium. All three MRA sequences leave the blood vessels as the main high-signal structures against a dark background. Using a special kind of computer processing technique called '**M**aximum **I**ntensity **P**rojection' (MIP), we can produce images which show the blood vessels (Figure 3.14), with a 3D effect when they are shown in a movie loop.

Warning: MRA is Not as Simple as it Looks!

MRA seems to be an easy technique for producing angiographic images without subjecting the patient to a risky intra-arterial procedure or ionizing radiation. However, it is not without problems. For example, time-of-flight sequences may not distinguish freshly thrombosed clots from flowing blood (because the methaemoglobin is starting to affect the MR signal), stenoses may be exaggerated in terms of length and severity, and very slow-flowing blood may disappear altogether. All these pitfalls will

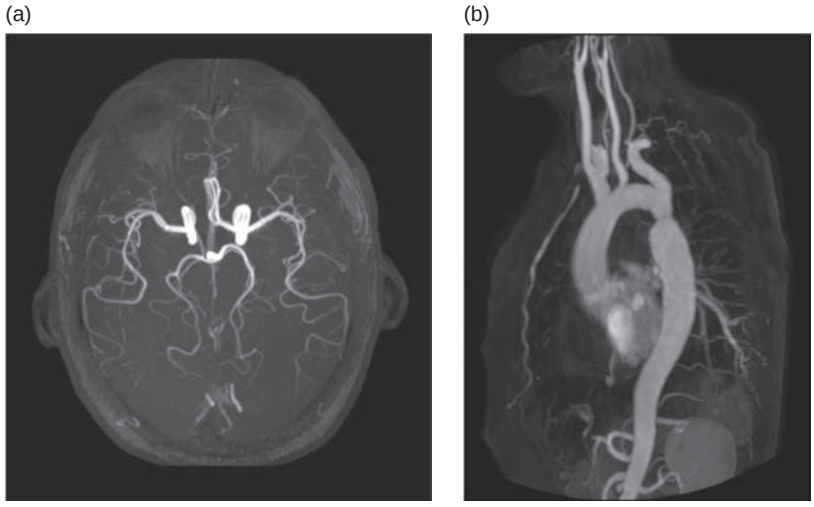

Figure 3.14 MR angiograms of (a) the Circle of Willis and (b) an aortic coarctation.

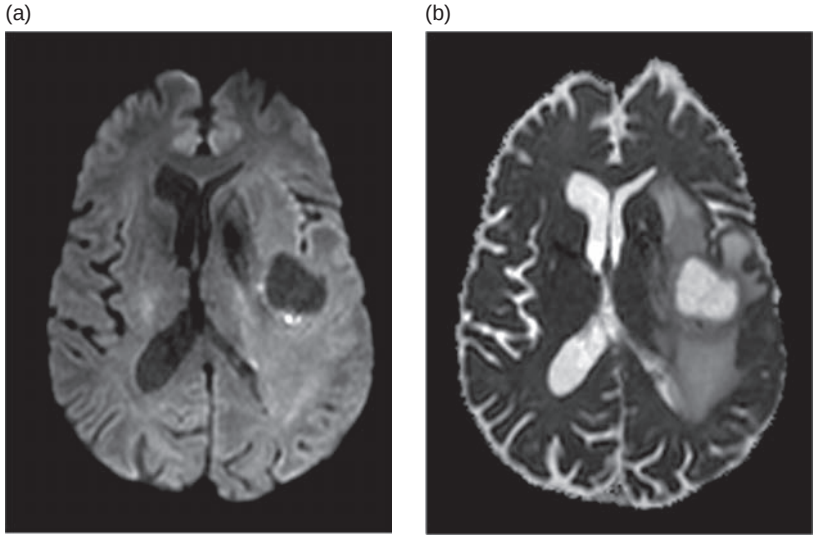

Figure 3.15 (a) DW images of brain tumour, with the lesion showing high signal. Notice that the CSF is not completely dark due to T_2 shine-through effect. (b) ADC map of the same slice, showing bright signal for CSF and mixed signal for the lesion.

be explained in detail in Chapter 15, along with ways of avoiding them. In spite of these potential problems, MRA is a common and very useful imaging technique which you will undoubtedly use regularly.

3.12 Diffusion-Weighted Images

Diffusion is a random process by which molecules move gradually within their environment. In MRI we are interested in the diffusion of water molecules, which changes in certain pathological conditions. For example in tumours which are rapidly proliferating, the local cell density becomes very high and the extracellular space becomes restricted. The protons in the extracellular space demonstrate reduced diffusion compared with normal tissues.

Diffusion-**W**eighted **I**maging (DWI) is almost always performed using a spin-echo **E**cho **P**lanar **I**maging (EPI) scan, which will be explained in Chapter 12. The diffusion sensitivity comes from a pair of very strong gradient pulses, one on either side of the refocusing RF pulse. These gradients have a large amplitude and duration, which means that they force the TE to be rather long, e.g. 80 ms. This means the DW images are also rather T_2-weighted, a phenomenon known as 'T_2-shine-through'. We can separate the T_2w effect from the diffusion effect by acquiring a

non-DW image as well as the DWI, and then combining these two images mathematically. The result is known as the ADC (**A**pparent **D**iffusion **C**oefficient) map, and this will be explained in more detail in Chapter 18.

Bulk fluids like CSF are dark on DW images, while normal brain tissue has an intermediate signal level. Restricted diffusion, such as we see in stroke or tumours, shows up as high signal intensity on DWI (Figure 3.15a). On the ADC images, the opposite is true: CSF shows up as very high signal (high diffusion) while restricted diffusion is dark (Figure 3.15b).

Diffusion is also widely used in body imaging, for example breast, liver or prostate. Focal tumours in these organs also tend to have high cell densities and show the same high signal on DWI as brain tumours or strokes. However, the EPI technique introduces geometric distortions which are particularly bad in these body areas, so it is rather difficult to achieve high-quality imaging.

See also:

- Details of T_1, T_2 and T_2^*, including the effects of gadolinium: Chapter 9.
- Gradient-echo sequences: Chapter 13.
- Fat suppression techniques: Section 7.3.
- MR angiography: Chapter 15.
- EPI and diffusion: Chapters 12, 18.

Further Reading

Bushong SC and Clarke G (2014) *Magnetic Resonance Imaging: Physical and Biological Principles*, 4th edn. St. Louis, MI: Mosby, chapter 7.

Hashemi RH and Bradley WG Jr (2010) *MRI: The Basics*, 3rd edn. Baltimore, MD: Lippincott, Williams & Wilkins, chapters 4–6.

Rinck PA (2007) *Magnetic Resonance in Medicine*, 5th edn. Berlin: ABW Wissenschaftsverlag GmbH, chapter 10.