Chapter 4

Lost in the Pulse Sequence Jungle?

4.1 Introduction

In Chapter 3 we saw how the image appearance can be manipulated by altering sequence parameters such as TR, TE, TI and flip angle to give T_1-weighted or T_2-weighted contrast. If only that was all there is to MRI! Unfortunately there are literally hundreds of pulse sequences. Every year at MR conferences around the world scores of new pulse sequences are launched and, in the tradition of the MR scientific community, all sport stylish acronyms.

Now, the trouble with acronyms is that despite sounding memorable and snappy (e.g. FLASH, HASTE, DIET, BRAVO, RESOLVE, etc.) it's virtually impossible to remember what they stand for, and therefore what they are designed to do. Moreover, MR manufacturers have the tendency to use different names for the same things (manufacturer conversion information is given in the tables of this chapter and the acronyms are spelled out in the Glossary). While the end-point of an acquisition can be expressed in terms of T_1 or T_2 weighting, there are numerous ways of achieving this – few destinations but many routes. So if you are lost in the pulse sequence jungle with a bewildering variety of sequence species, and cannot see the wood for the trees, this chapter is for you.

You will see that:

- there are two major pulse sequence families: spin echo (SE) and gradient echo (GE);
- gradient-echo sequences are generally faster;
- there are ways of speeding up spin echo;
- sequences generally exploit T_1 or T_2 contrast;
- gradient-echo sequences are good for studies with gadolinium-based contrast agents, particularly in the body or for bright fluid imaging, for example in cardiac studies.

4.2 Anatomy of a Pulse Sequence

A pulse sequence has several functions. These include generating suitable contrast between tissues (Chapter 3), forming an image, having an appropriate scan time, for example, within a breath-hold, and avoiding artefacts, e.g. motion, flow. You'll get a lot more detail in later chapters. For now, be aware that there will always be *RF pulses* and *gradients*, one of which will always be a read or *Frequency-Encode* (FE) gradient. There will almost always be one or two sets of *Phase-Encode* (PE) gradient pulses and some form of *slice selection* or slab selection. Every sequence also contains the basic timing parameters: TR, measured in milliseconds (ms), and TE (also in ms) are shown in Figure 4.1. TR is the repetition time between the acquisition of different lines of the raw data, or between excitations (making the signal). TE is the time that each signal or echo is measured following its initial generation or excitation.

4.2.1 Examinations, Sequences and Parameters

In the scanner's user interface, whole examinations are grouped together according to body part and clinical application or pathology (and sometimes coil). An *examination* or a *program* consists of a list of *sequences* to carry out the examination. Examples of standard examinations are given in clinical boxes in Chapter 3.

Each sequence within the examination, for example T_1-weighted, T_2-weighted, diffusion-weighted, will contain default *parameters* such as orientation, number of slices, slice width, number of signal acquisitions or averages, and the timing parameters: TR, TE, TI (where applicable). These have been either pre-selected by the manufacturer or customized on site to give images of the desired diagnostic quality and utility. Common sequence parameters are shown in Figure 4.2. Each

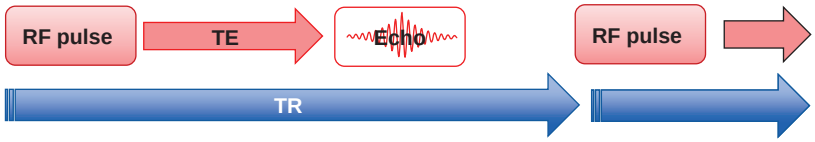

Figure 4.1 Basic sequence structure. The time between repeated RF excitations is TR. TE is the time after the RF excitation that the echo signal is measured.

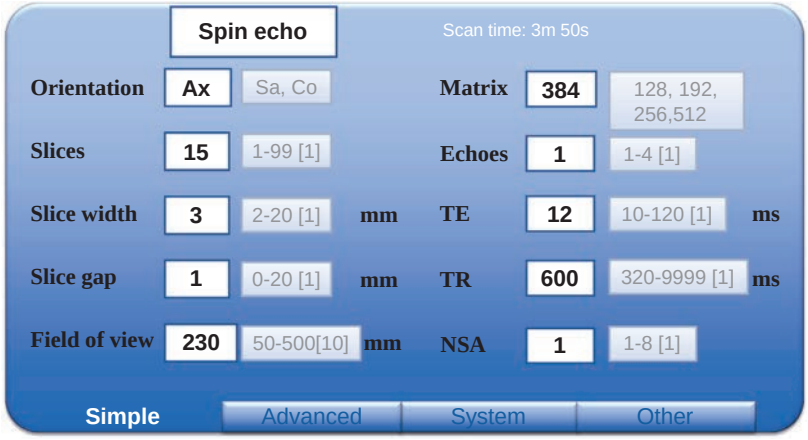

Figure 4.2 Sequence parameters shown in a mock-up of a user interface. The selected parameter values are in bold type, the possible range in grey and the incremental changes permitted shown in brackets. A user interface will usually consist of a number of pages or cards or tabs, shown along the bottom or top of the page.

parameter will have a default value and a range of user-selectable values. Sometimes the parameters are arranged on different *tabs* or *cards*.

In the next two chapters we will learn much more about making parameter changes. For now we will only concern ourselves with a basic subset of parameters: TR, TE, TI, **E**cho **T**rain **L**ength (ETL), 2D or 3D, and scan time. Scan time is determined by TR, along with the number of lines (N_{PE}) in the image and **N**umber of **S**ignal **A**verages (NSA, called NEX on GE Healthcare systems):

$$\text{Scan time} = \text{TR} \times N_{PE} \times \text{NSA}$$

For example, using the values shown in Figure 4.2, the prescribed scan time would be $[(600\,\text{ms} \times 384 \times 1) \div 1000]$ seconds, or 3 min 50 s.

Additionally, various other features may be added to the basic sequence structure to ensure that scans are diagnostic. These are listed in Box 'Sequence Options' and explored more deeply in later chapters.

Sequence Options

In addition to providing the basic image contrast, sequences often incorporate features to avoid certain artefacts or to reduce unwanted signals. These can include:

- *spatial saturation*, to remove unwanted artefact-producing signals (e.g. from breathing). Usually there will be a choice of several saturation bands, all freely selectable in space;
- *fat suppression* or saturation;
- *magnetization transfer saturation* to improve contrast, or reduce background signal intensity in cerebral angiography;
- *magnetization preparation*, e.g. inversion pulses as the start of the TR period;
- *magnetization restoration*, e.g. driven equilibrium pulses at the end of the TR period.

These are repeated within every TR period so, referring to Figure 4.3, reduce the time available for each slice and also the number of slices possible.

4.2.2 The Pulse Sequence Family Tree

A great deal of the variety of MR sequences arises from the need to generate particular types of image contrast and also to speed up MR acquisitions. It's a complicated family, but like human families with maternal and paternal branches, there are basically two types of sequence: spin echo (SE) and gradient echo (GE). Helpfully there are also two basic contrast mechanisms: T_1 and T_2, but like real families there is often a hidden complexity to sequence characteristics and contrast behaviour. Figure 4.4 shows the generic pulse sequence family tree for spin echo, with an indication of acquisition speed and type of contrast achievable.

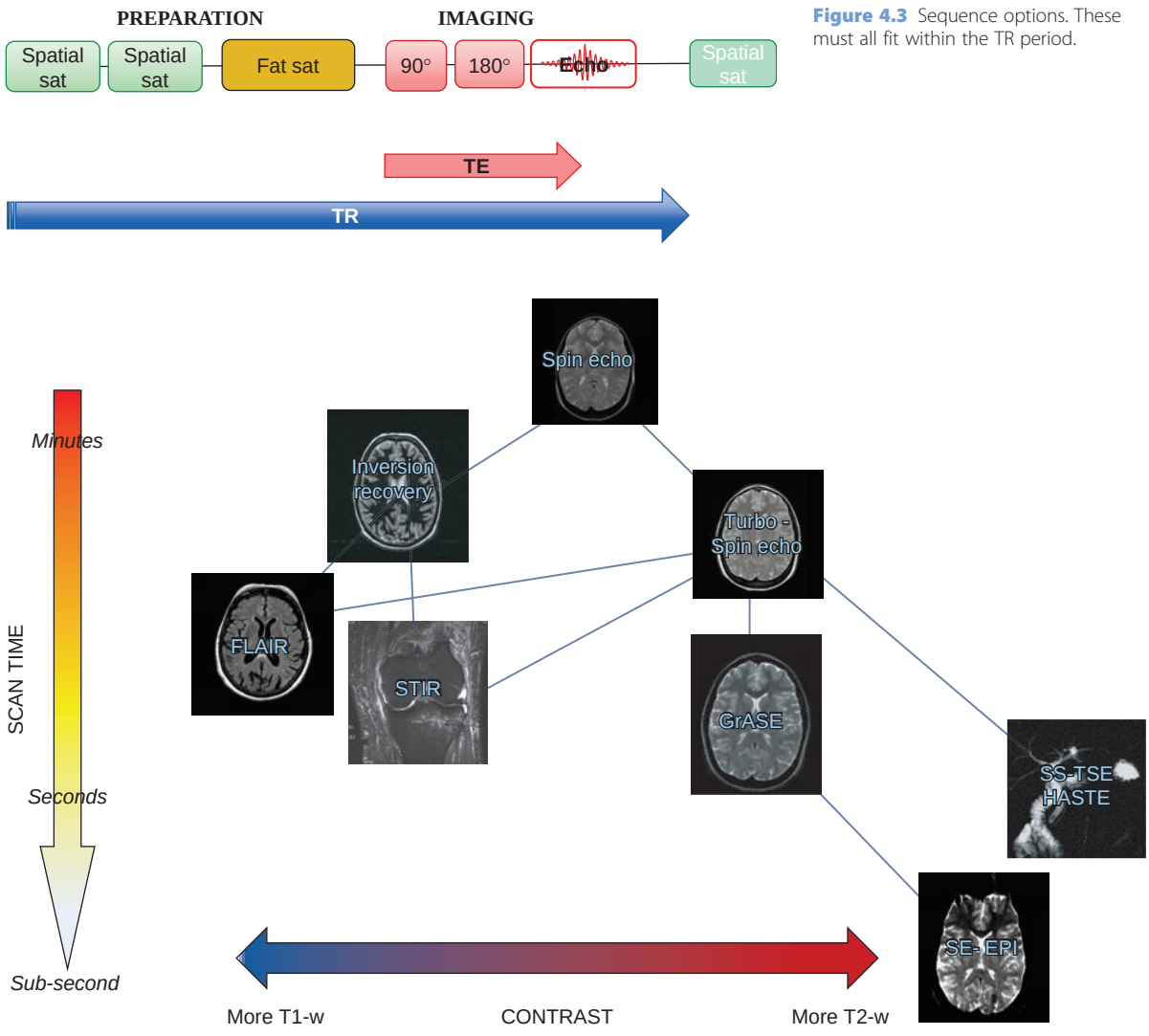

Figure 4.3 Sequence options. These must all fit within the TR period.

Figure 4.4 Pulse sequence family tree: spin-echo branch. Acquisition time is indicated vertically, with indicative contrast behaviour shown horizontally.

In terms of increasing speed and complexity the spin-echo branch of the family contains **T**urbo or **F**ast **S**pin **E**cho (TSE/FSE), turbo **GR**adient **A**nd **S**pin **E**cho (GRASE), single-shot TSE or **HA**lf-Fourier **S**ingle-shot **T**urbo spin **E**cho (HASTE) and **S**pin-**E**cho **E**cho **P**lanar **I**maging (SE-EPI). Other variants of spin echo include **FL**uid **A**ttenuated **I**nversion **R**ecovery (FLAIR) and **S**hort **TI** **I**nversion **R**ecovery (STIR). These sequences are usually applied in two dimensions, i.e. in slices or sections, as in CT. Three-dimensional fast/turbo spin-echo sequences have recently become viable. These can provide high-resolution, isotropic images suitable for **M**ulti-**P**lanar **R**eformats (MPR). The commercial names of these sequences are shown in Table 4.1.

4.3 Take Me for a Spin (Echo)

Spin echo is the standard, vanilla-flavour MR pulse sequence and, rather like ice-cream, we find that it is now often surpassed by more exotic flavours although it remains the standard sequence for T_1-weighted brain imaging. It also forms the basis of the SE sequence family tree, with its parameters TR and TE respectively controlling the T_1 and T_2 weighting of the image.

The advanced Boxes 'Magnetization and the Meaning of Life' and 'Making a Spin Echo' show the origin of the MR signal and how the echo is formed, but you can just as easily leave the details of how the echo is made until later (Chapter 9). Consider for now that to

Table 4.1 Spin-echo sequences manufacture comparison chart. The acronyms are defined in the Glossary

Generic name	GE Healthcare	Hitachi	Philips	Siemens	Toshiba
Spin echo	SE	SE	SE	SE	SE
RARE	FSE	FSE	TSE	TSE	FSE
IR-RARE	FSE-IR	FIR	IR-TSE	Turbo-IR, TIR	Fast IR
Short TI inversion recovery	STIR	STIR	STIR	STIR	Fast STIR
Long TI inversion recovery for CSF suppression	FLAIR	FLAIR	FLAIR	Turbo-dark fluid	Fast FLAIR
Single-shot RARE	SS-FSE SSFSE-IR		SS-TSE	SS-TSE HASTE	DIET, FASE, SuperFASE
Gradient and spin echo (GRASE)			GRASE	TGSE	
RARE driven equilibrium (90° flip back)	Fast Recovery FSE	DE-FSE	DRIVE	RESTORE	T_2 plus FSE
3D RARE with variable flip angle	CUBE	isoFSE	VISTA, 3D-VIEW	SPACE	3D mVOX
Radial FSE	PROPELLER	RADAR	MultiVane	BLADE	JET
Echo planar imaging	EPI	EPI	EPI	EPI	EPI

make an MR signal we have to put in a pulse of (radiofrequency) energy and that, analogous to ultrasound, the tissue responds by generating an 'echo' which can be detected by the scanner through the MR coil (Figure 4.5). The time between the initial (excitation) pulse and the detection of the echo is called 'echo time' or TE, while the time between successive excitation pulses is the repetition time, TR. As we saw in Chapter 3, TR controls the T_1 contrast, while TE controls the T_2 contrast. Spin-echo sequences have the advantage that the image appearance is solely dependent upon the properties of the tissue, and not significantly influenced by the quality of the magnetic field, or inhomogeneity, in the scanner.

Magnetization and the Meaning of Life

When the patient is placed within the bore of the magnet, they become very, very slightly magnetic (Figure 4.6). For example, in a 1.5 T scanner, the average induced magnetic field, or magnetization of a typical adult head, is around 20 microtesla (μT) – less than half the earth's magnetic field and 75 000 times less than the scanner's magnetic field. This magnetic field points in the direction of, or aligns with, the direction of the scanner's field, along the head-foot or *z* axis.

In order to measure this tiny magnetization, it is necessary to tilt it away from the *z* axis. This is achieved by applying a radiofrequency (RF) pulse at the resonant or Larmor frequency f_0 given by

$$f_0 = \gamma\!\!\!^{-} \cdot B_0$$

where B_0 is the scanner's magnetic field measured in tesla, $\gamma\!\!\!^{-}$ (pronounced 'gamma bar') is the gyromagnetic ratio, a constant equal to approximately 42 MHz T^{-1}, and f_0 is expressed in megahertz (MHz).

Once tipped away from the B_0 direction (*z*), the magnetization M can be detected by an appropriately set-up coil. The signal detected is proportional to the transverse, or *xy* component of *M*, denoted M_{xy}. The maximum signal is achieved following a pulse which tilts or flips M through 90 degrees. This is called a 90° pulse.

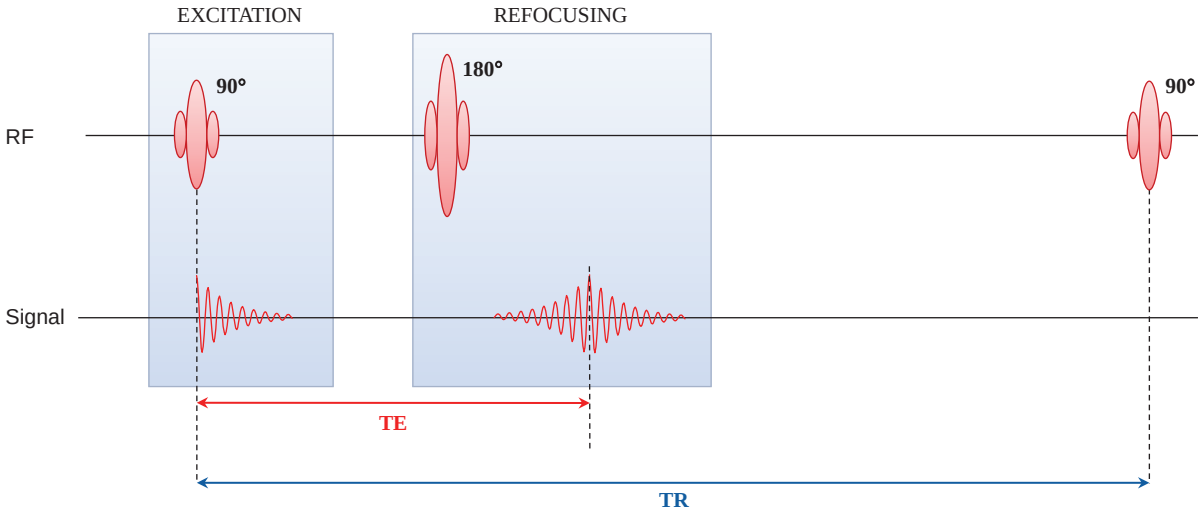

Figure 4.5 Simple spin-echo sequence (showing only RF pulses).

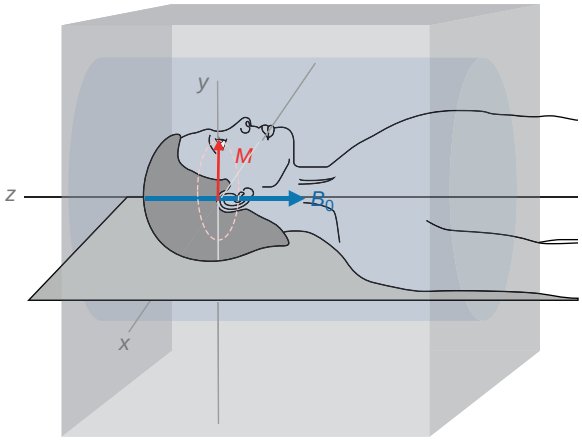

Figure 4.6 The patient's magnetization when placed in the magnet. This is flipped into the transverse plane (xy) to make a signal.

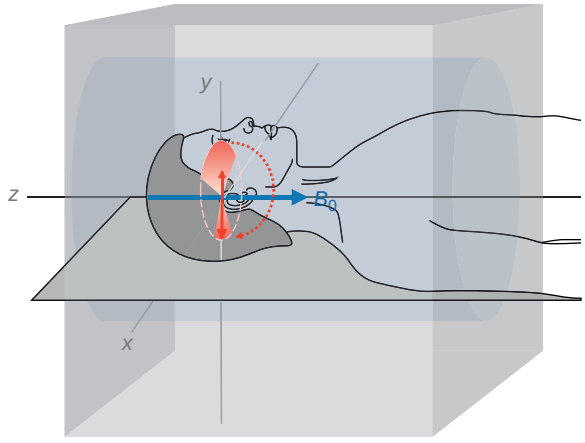

Figure 4.7 The formation of a spin echo.

Making a Spin Echo

Once created, the signal does not last very long (typically a few tens of milliseconds). It reduces or decays because transverse magnetization M_{xy} in different positions within the scanner experience slightly different magnetic fields – and thus produce signals at slightly different frequencies. This is equivalent to parts of M_{xy} diverging or fanning out in the xy-plane (Figure 4.7), where some of M_{xy} has lower frequencies (or a phase lag) and other parts have higher frequencies (phase advance).

By applying a 180° or refocusing pulse the effect of the spread of frequencies can be reversed. The 180° pulse twists the 'fan' of magnetization vectors about the *x* axis, in such a way that parts which had the largest phase lag (slowest), now have the greatest phase advance. Similarly, parts which were

most advanced (fastest) are now moved to a position where they are most retarded. In this way, after a time TE equal to double the time between the two RF pulses, all the transverse magnetization coincides along the *x* axis and a signal maximum, the spin echo, is obtained. Thereafter the dephasing, or signal decay, occurs again and the echo fades away. Spin echo corrects for signal loss due to static field inhomogeneities, with any signal decay indicating the true transverse or T_2 relaxation behaviour of the tissue.

Spin echo formation is often considered in terms of the 'runners on the track' analogy. In this a group of contestants start a race on the sound of a gun (the 90° pulse). Having different levels of fitness and ability they all spread out. When the gun is fired again (a 180° pulse) they all have to double back the way they came. In this way the slowest runners, who have the least far to go, and the fastest who have covered more ground, all arrive back at the start together (making the echo).

4.3.1 Turbo Spin Echo: The Work Horse

In order to make an image, the basic pulse–echo sequence has to be repeated (for as many times as there are lines in the image). As we are using TR to control the image contrast we therefore don't have proper control of the scan time: we cannot reduce it by shortening TR as that will affect the image appearance. In **T**urbo or **F**ast **S**pin **E**cho (TSE, FSE), multiple signal echoes are collected following each excitation pulse (Figure 4.8) and therefore the scan time can be reduced by the **T**urbo **F**actor (TF) or **E**cho **T**rain **L**ength (ETL). Thus for an ETL or TF of 8, the scan time is reduced by eight times. In practice echo train lengths vary from 3 to 256. The generic name for this type of SE sequence is **R**apid **A**cquisition with **R**elaxation **E**nhancement (RARE). We will refer to it as TSE.

TSE has become the standard sequence for T_2-weighted imaging. It produces excellent T_2 contrast by the combination of long TR (to avoid T_1 effects) and variable TE to control the extent of T_2 weighting. In Chapter 12 we shall see how this is achieved in practice, but for now we can think of it as an SE used for T_2-weighting. Example images of SE-type sequences are shown in Box 'Brain Sequences'.

Brain Sequences

Here, we look at the sequences within a typical brain examination. These are for illustrative purposes only. Actual clinical sequences and parameters used will depend upon the diagnostic question and your institutional protocols.

Scan	Sequence	Typical parameters	Comments
Axial T_1w (Figure 4.9a)	SE	Short TR (400–700 ms). Short TE (<15 ms). 20–30 slices, 3–5 mm slice, FOV 230 mm, matrix 320 × 256.	The short TR gives good T_1 weighting. The sequence can be used pre-contrast, demonstrating sub-acute haemorrhage and infarct necrosis. Post-contrast it shows ring-enhancing lesions such as lymphoma, glioblastoma and necrotic metastases.
Coronal T_2w (Figure 4.9b)	TSE	Long TR (>4000 ms). Long TE (>80 ms). Turbo factor ~ 11–15. Slices etc. as above	TSE is used to mitigate the time penalty of a long TR, required for good T_2 weighting. Good for detection of tumours, infarct, inflammation and infection.
Axial T_2w FLAIR (Figure 4.9c)	FLAIR	Very long TR (>8000 ms). Long TE (>80 ms). TI ~ 2400 ms. Slices etc. as above.	Nulls signal from CSF, enables detection of small lesions with elevated T_2 including MS plaques.
Axial DWI (Figure 4.9d)	Spin echo EPI	b-factor 500–1000, TR and TE as required. 20 slices, 5 mm. Matrix 128 × 128.	Lower-resolution scan with diffusion weighting. Detection of hyper-acute stroke. Distinguishes acute ischaemia from chronic infarct.

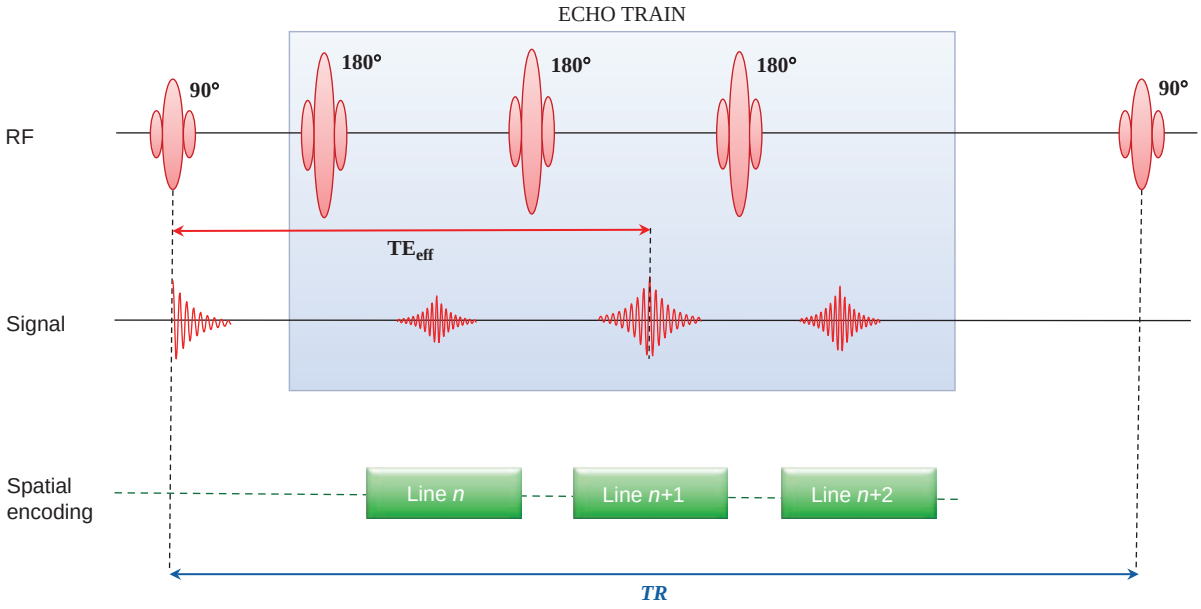

Figure 4.8 Basis of turbo spin echo. Several lines of data (in this example, three) are acquired for every TR period, reducing the overall scan time by the echo train length or turbo factor.

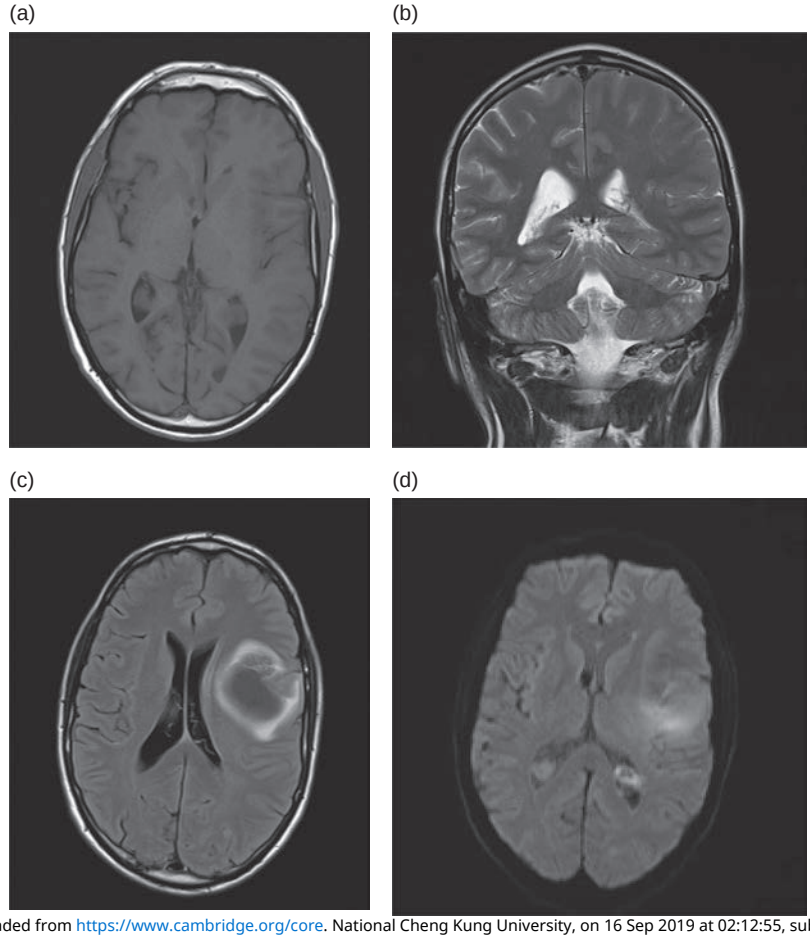

Figure 4.9 SE type images (a) T_1-weighted SE, (b) T_2-weighted TSE, (c) FLAIR with T_2-weighting, (d) DWI-EPI. See Box 'Brain Sequences' for details.

4.3.2 TSE Variants

A number of parameter options are available to further refine the use of TSE sequences. One of these is to add an *inversion pulse* before the excitation. This sequence is called **I**nversion **R**ecovery (IR) and results in very strong T_1 weighting. IR may also be used to remove unwanted signals from the image, such as fat as in STIR or cerebrospinal fluid as in FLAIR. To achieve this, an additional parameter TI, the inversion time between the initial 180° pulse and the 90° excitation pulse, is set. Because the value of TI determines the ability of the sequence to null signals from either fat or CSF, it should not usually be altered from the default value in the protocol.

Another option, particularly useful in T_2w imaging, is to use an RF pulse to speed up the recovery of the signal, thereby enabling a reduction in TR. This so-called *driven equilibrium* pulse is a 90° pulse applied after the MR signal has been acquired and just before the next excitation pulse. Figure 4.10 shows how these options add to a basic TSE sequence.

Some TSE sequences can acquire the whole image with a very long echo train following a single excitation pulse. These may be called HASTE or **S**ingle-**S**hot FSE/TSE (SS-TSE). These sequences are very useful for imaging fluid structures, e.g. the biliary system in **MR C**holangio-**P**ancreatography (MRCP) examinations. TSE can operate in either two-dimensional (2D) or three-dimensional (3D) mode. The 3D mode enables high-resolution 3D images to be acquired, and may be called CUBE, 3D-VIEW or SPACE on your scanner.

One of the downsides of TSE is its sensitivity to movement artefacts. To reduce this, radially acquired TSE can be used. Sometimes known as PROPELLER, MultiVane, BLADE or JET, the sequence offers more limited image contrast, primarily T_2, but proves almost immune to patient movement.

Knee Sequences

Here we look at the sequences within a typical knee examination. These are for illustrative purposes only. Actual clinical sequences and parameters used will depend upon the diagnostic question and your institutional protocols.

Scan	Sequence	Typical parameters	Comments
Sagittal PDw (Figure 4.11a)	TSE	Long TR >2000 ms. Short TE <30 ms. 20–30 × 3 mm slices, FOV 160 mm, matrix 320 × 256.	Good for visualizing anterior/ posterior cruciate ligaments and anatomical overview: muscle, cartilage, bone marrow, fat.
Coronal T_2w fat sat (Figure 4.11b)	TSE with fat sat and driven equilibrium pulse	Intermediate TR >1000 ms. Long TE >80 ms. Turbo factor ~11–15. Slices and FOV as above.	Fat sat removes bone marrow signal, and enables assessment of bone bruises. Good for evaluating menisci and cartilage.
Coronal STIR (Figure 4.11c)	STIR (TSE)	Long TR >4000 ms. Short TE <20 ms. TI ~140 ms. Slices and FOV as above.	STIR nulls the fat. Can be used in place of TSE fat sat. Gives 'appearance' of T_2-weighting.
Axial or sagittal T_1w or PDw GE (Figure 4.11d)	3D FLASH with water excitation or fat sat or DESS[1]	Short TR <20 ms. Short TE <10 ms. Small flip angle <40°. FOV as above, slices 1–2 mm.	Enables semi-quantitative investigation of chondral cartilage integrity and thickness. Can view in multiple planes.

[1] See Section 13.3.4.

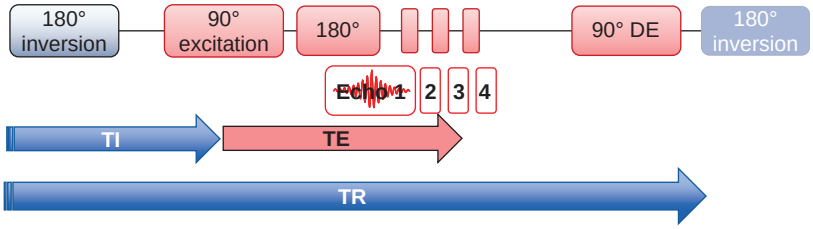

Figure 4.10 TSE variants. An inversion pulse with its timing parameter TI can be added to the beginning of the TR period to control T_1 weighting or null CSF or fat. A driven equilibrium magnetization restoration pulse can be added at the end of the TR period to enhance the recovery of the magnetization (signal) and allows a shorter TR.

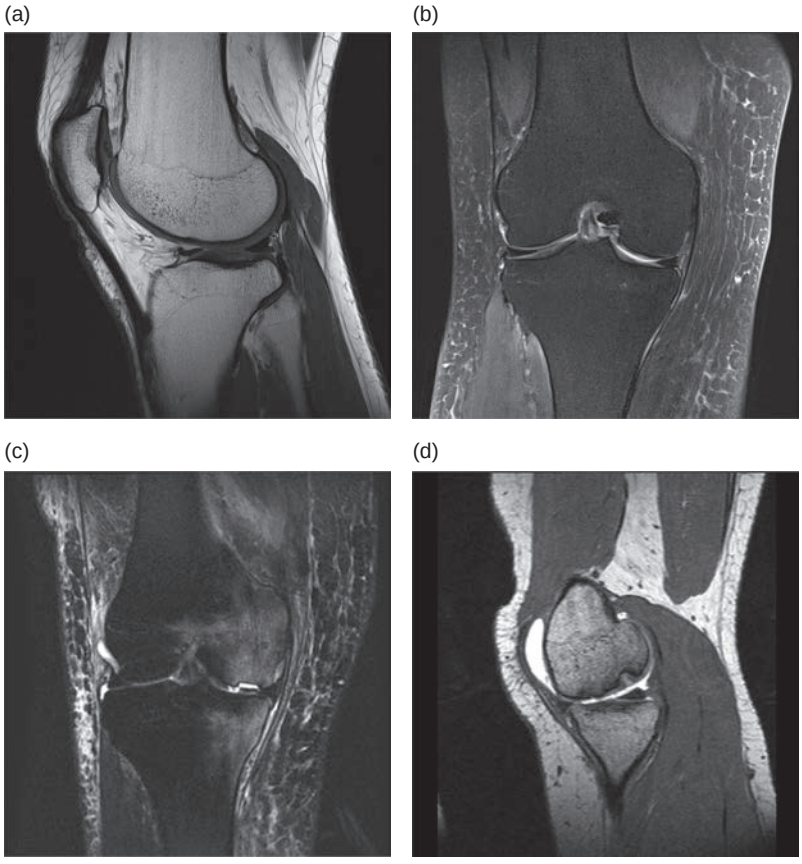

Figure 4.11 (a) PD-TSE, (b) TSE with fat sat and DRIVE, (c) Coronal STIR (d) 3D DESS.

4.4 The Other Branch of the Tree: Gradient Echo

The family on the gradient-echo side is somewhat more complex: spoiled or incoherent gradient echo, rewound or coherent gradient echo and time-reversed GE plus some hybrid sequences, most with options for 2D or 3D acquisition (shown in Figure 4.12). Contrast tends to be T_1- or T_2^*-weighted and sometimes a mixture of T_1 and T_2. The sequences in this branch will commonly be used for MR angiography, contrast studies, breath-hold imaging and high-resolution 3D imaging. EPI is the ultimate in terms of scanning speed, collecting a whole slice in under 100 ms. In this chapter we will introduce the most popular forms of gradient echo: spoiled GE and rewound GE, and their offspring. Table 4.2 shows the commercial names for these sequences.

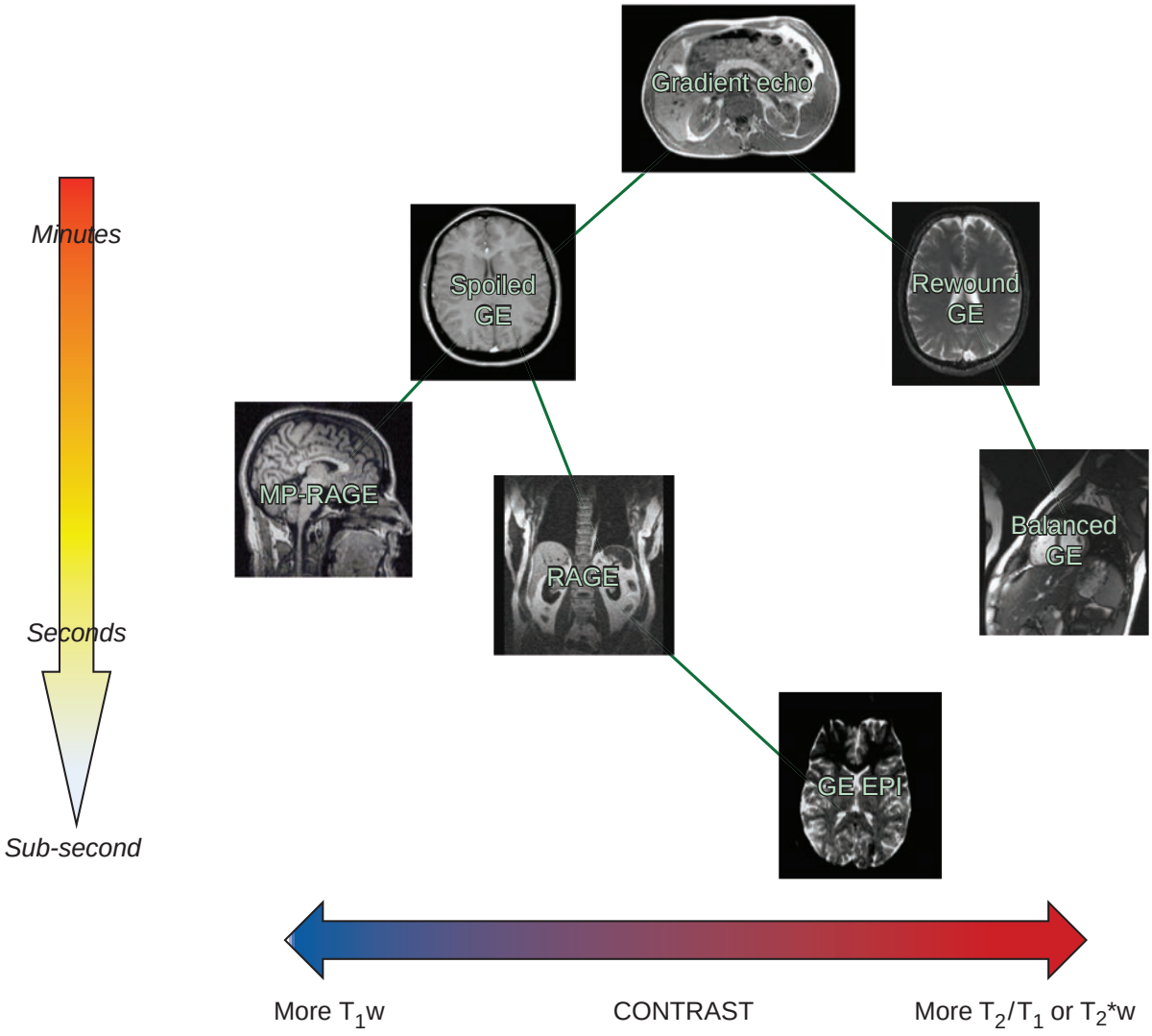

Figure 4.12 Pulse sequence family tree: gradient-echo branch. Acquisition time is indicated vertically, with indicative contrast behaviour shown horizontally.

4.4.1 Making the Grade: Gradient Echo

Gradient **E**cho (GE) or **G**radient **R**ecalled **E**cho (GRE) was originally conceived of as a way of reducing scan time, by reducing TR without adversely affecting the T_1 contrast of the image. In GE a new parameter, the flip angle, α (alpha) is introduced. As we saw in Chapter 3, this mainly controls the T_1 appearance of the image. As in spin echo, an echo signal is detected in the coils. However, one major difference is that this echo is produced by a magnetic field gradient rather than by a refocusing RF pulse. This results in the signal existing for a much shorter time than in SE, and this limits the maximum value of TE that can be used, and consequently the T_2 weighting that may be achieved. Rather, in GE we say that the signal is T_2^*-weighted. Figure 4.13 shows a simplified GE sequence with the timing parameter. Box 'Making a Gradient Echo' explains how the echo is formed, but you can leave the details of this till later if you wish.

Table 4.2 Gradient-echo sequences and sequence names

Generic name	GE Healthcare	Hitachi	Philips	Siemens	Toshiba
Spoiled gradient echo	SPGR	RSSG	T1-FFE	FLASH	FE
Rewound gradient echo	GRE	SARGE, SG	FFE	FISP	FE/PFI
Fully rewound gradient echo	FIESTA	BASG	bFFE	TrueFISP	True SSFP
Phase-cycled rewound gradient echo	FIESTA-c, COSMIC	PBSG		CISS	
Time reversed gradient echo		TRSG	T2-FFE	PSIF	SSFP
Multi-echo combined GE	MERGE		mFFE	MEDIC, DESS	
2D ultrafast GE	FGRE, FSPGR	RGE	TFE	Turbo-FLASH	Fast FE
3D ultrafast GE	BRAVO	MP-RAGE	3D TFE	MP-RAGE	3D Fast FE
Volume interpolated 3D-GE	LAVA	TIGRE	THRIVE	VIBE	QUICK 3D
Echo planar imaging	EPI	EPI	EPI	EPI	EPI

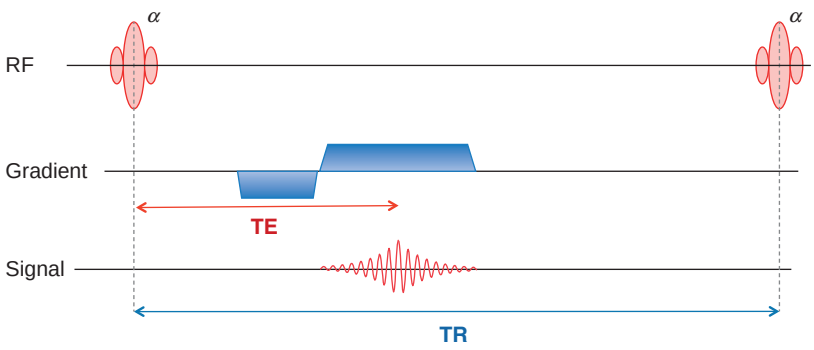

Figure 4.13 Simple gradient-echo sequence (showing only 1 gradient).

Making a Gradient Echo

In gradient echo, the transverse magnetization M_{xy} is artificially dephased by introducing a deliberate and controlled linear variation in magnetic field across the imaging field of view (FOV). This is applied in the form of a gradient pulse, usually of a few milliseconds' duration (Figure 4.14). This changes the resonant frequency across the FOV and will result in a very rapid dephasing of different parts of the transverse magnetization M_{xy} and loss of measurable signal.

If the effect of the gradient is reversed, by changing the algebraic sign of the pulse, parts of M_{xy} that were in a lower magnetic field now find themselves in a higher field, and vice versa, with the result that at some point in time, the echo time TE, they will all be aligned again, forming the peak of the gradient echo. The relaxation behaviour of signal in gradient echo is determined by T_2^* (pronounced 'tee two star') which includes the T_2 properties of the tissue, but also is degraded by the effects of the static field imperfections or inhomogeneities and differences in tissue composition.

T_2^* differs from T_2 in that it relates not just to the tissue properties, but also to the quality of the magnetic field or inhomogeneity of the scanner. This latter property often dominates the signal characteristics, hence the shorter TE (compared with SE).

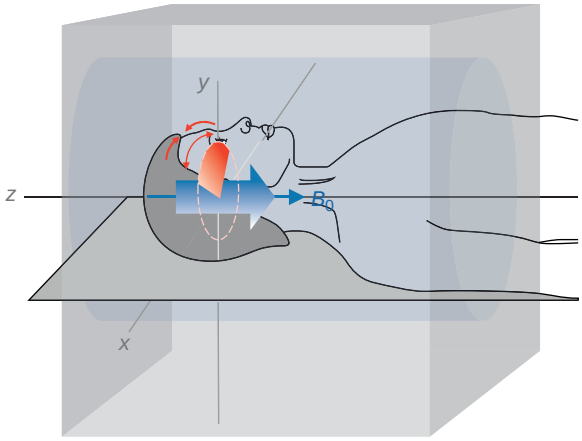

Figure 4.14 Making a gradient echo.

4.4.2 Spoiled Gradient Echo

Gradient-echo sequences can be used to give fast T_1-weighted sequences in either 2D or 3D. They are particularly suited to dynamic gadolinium contrast enhanced studies (see Box 'Abdomen Sequences'). Depending upon your scanner, the basic T_1-weighted (or spoiled) gradient-echo sequence may be called FLASH, T_1-FFE, or SPGR. Note, however, that these are all basically the same thing. The marketing department of the scanner company wants you to think that they have a unique feature (and sometimes they do, but not in this instance!).

Just as GE does not compensate for inhomogeneity in the scanner's static magnetic field (denoted ΔB_0, pronounced 'delta bee nought'), neither does it correct for inhomogeneities in tissue composition, e.g. between water and fat. This may

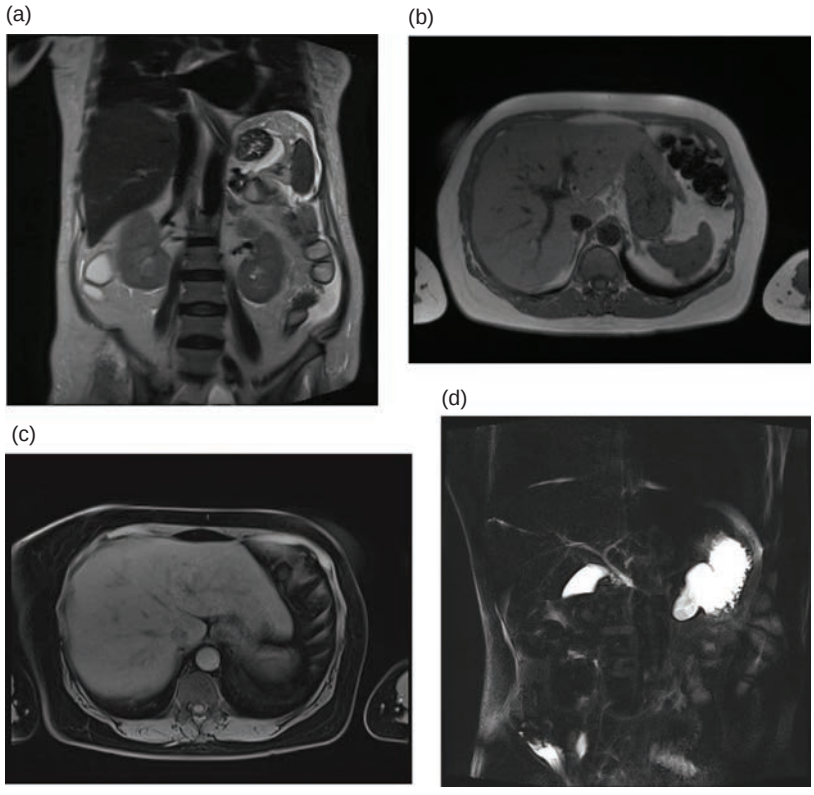

Figure 4.15 Sequences used in the abdomen: (a) HASTE, (b) 2D FLASH (c) 3D-VIBE (d) thick slab MCRP using HASTE.

result in the signals from water and fat either combining or cancelling each other. For this reason it is important not to change TE in gradient echo without careful consideration on its effect on the image appearance. In the abdomen, in-phase (IP) and out-of-phase (OP) imaging can be useful to delineate intra-organ fat.

4.4.3 Rewound Gradient Echo

The other common type of gradient echo is called rewound (or refocused) gradient echo. This is partway between a proper spin-echo and a gradient-echo sequence, and the contrast is generally a mixture of T_2- and T_1-weighted. We shall see later (Chapter 13) that the image contrast often favours a bright fluid appearance, which makes the sequence popular for angiography or cardiac applications. Rewound GE sequences may be called FISP, FFE or GRE. The sequence may be performed in 2D or 3D, and the short TR makes it particularly suitable for 3D scanning.

A particular variant of this sequence is the balanced version, also called True-FISP, balanced FFE or FIESTA. These are especially popular for bright-blood cardiac imaging where blood is bright in contrast to the darker myocardial muscle. In balanced gradient echo, TE may not be independently set from TR, but is always equal to exactly half the value of TR. The images may suffer from artefacts around the edges of the field of view.

4.4.4 Ultrafast GE Sequences

Just as in SE, there is a limit to how fast we can run gradient-echo sequences and still obtain enough signal with suitable contrast to make a diagnostic image. This restricts the shortest useful TR, and thus the shortest scan time achievable. If we were to use a very short TR, with a small flip angle, the image would have a very flat (proton density) appearance and would appear very noisy with low signal intensity. However, we can use pre-pulses to improve SNR and contrast, e.g. to re-introduce T_1 weighting we would add an inversion pulse at the start of the sequence. These sequences carry the generic name RAGE (**R**apid **A**cquisition **G**radient **E**cho). RAGE sequences are useful for very fast T_1-weighted imaging, for example, in dynamic Gd-based contrast studies in the abdomen. T_2-weighted versions are also possible, although they are less common. RAGE can be optimized for fast 3D breath-hold abdominal examinations, and may be called VIBE, LAVA or THRIVE.

Abdomen Sequences

Here we look at the sequences you might encounter in abdominal imaging. These are for illustrative purposes only. Actual clinical sequences and parameters used will depend upon the diagnostic question and your institutional protocols.

Scan	Sequence	Typical parameters	Comments
Coronal T_2w SS-TSE (Figure 4.15a)	HASTE or SS-TSE	Moderate TR >1000 ms. Long TE >100 ms. 30 × 5 mm slices, FOV 400 mm, matrix 256 × 192.	Quick sequential scanning, not overly affected by movement due to acquisition of a whole slice per shot. Bright T_2w indicates cysts, hepatocellular carcinoma (HCC) and metastases.
Axial T_1w (Figure 4.15b)	2D Spoiled GE	Short TR <200 ms. Short TE e.g. 4.2 ms (IP), 2.1 or 6.3 ms (OP) at 1.5 T. Slices and FOV as above.	Spoiled GE is used to obtain T_1w within a breath-hold. Acquired in- and out-of-phase. Useful to discriminate adenoma or fatty infiltration due to cirrhosis.
Axial T_1w volume (Figure 4.15c)	VIBE, THRIVE, LAVA, etc.	Very short TR <10 ms. Very short TE <3 ms. 60 × 3 mm slices, FOV 400 mm, matrix 320 × 224.	Acquired as a 3D T_1-weighted volume. Can be timed to give arterial, venous and equilibrium phases in the liver. Early enhancement for HCC, hepatic adenoma and cholangiocarcinoma. Metastases show persistent enhancement.
MRCP (Figure 4.15d)	T_2w HASTE/SS-TSE or 3D-TSE	Long TR >4000 ms. Very Long TE >500 ms. For 2D use thick slices >50 mm. For 3D use thin slices (<3 mm). Very high turbo factor >128.	Very long TE ensures only fluid signal in the biliary system is visible. Thick slabs are acquired as obliques. Thin slices can be viewed as MIP.

4.5 Echo Planar Imaging

There are two points in the family tree where spin echo and gradient echo are linked, hybrid sequences which cannot be classified as just one or the other. The first is GRASE, which we have placed in the spin-echo branch, even though it is a true hybrid sequence generating both spin echoes and gradient echoes. The reason for this is that the contrast which GRASE generates is closer to a spin-echo or TSE contrast, i.e. T_2-weighted rather than T_2^*-weighted.

The other sequence is echo planar imaging (EPI), which can exist either as a hybrid SE-EPI or as a pure gradient echo version. EPI is used in applications such as perfusion, diffusion or functional MRI, where extreme acquisition speed in a single shot is required. Spin-echo EPI is used for DWI, while gradient echo EPI (or simply EPI) is used for perfusion and fMRI. Scan times can be less than 100 ms, thus freezing all physiological motion. Generally these are applied with a relatively low spatial resolution and the images suffer from particular artefacts (considered further in Chapters 12 and 13). On their own they are seldom diagnostic, but lend themselves to further image processing to produce quantitative maps of diffusion, perfusion or brain oxygenation (Chapter 18).

4.6 The Pulse Sequence Traveller

Needing to choose a pulse sequence? At this point we refer you back to Figure 4.4 and Figure 4.12, but this time you should view it more as a route map than a family tree. First, decide your destination – T_1, T_2 or PD weighting, etc. Then decide how you want to get there and how fast you want to go. Finally, think about potential pitfalls; for example, what artefacts you might encounter, or what limitations there are on resolution or slice number. Remember that as in real travel, when visiting different countries, different languages are spoken. You can think of Table 4.1 and Table 4.2 as your pulse-sequence phrase book. Bon voyage!

See also:

- Getting in Tune: Resonance and Relaxation: Chapter 9.
- Acronyms Anonymous I: Spin Echo: Chapter 12.
- Acronyms Anonymous II: Gradient Echo: Chapter 13.
- Glossary – for explanation of sequence acronyms.

Further Reading

Brown MA and Semelka RC (1999) 'MR imaging abbreviations, definitions and descriptions: a review'. *Radiology* 213:647–662.

Elster AD and Burdette JH (2001) *Questions and Answers in Magnetic Resonance Imaging*, 2nd edn. London: Mosby-Yearbook, chapters 5 and 12. Also on the web at http://mri-q.com [accessed 23 March 2015].

Liney G (2011) *MRI from A to Z*, 2nd edn. London: Springer-Verlag.