5 MRI SEQUENCES

An MRI sequence is an ordered combination of RF and gradient pulses designed to acquire the data to form the image. In this chapter I will describe the basic gradient echo, spin echo and inversion recovery sequences used in MRI.
The data to create an MR image is obtained in a series of steps. First the tissue magnetisation is excited using an RF pulse in the presence of a slice select gradient.
The other two essential elements of the sequence are phase encoding and frequency encoding/read out, which are required to spatially localise the protons in the other two dimensions. Finally, after the data has been collected, the process is repeated for a series of phase encoding steps.
The MRI sequence parameters are chosen to best suit the particular clinical application. The parameters affecting soft tissue contrast are described, and advanced sequences such as STIR, FLAIR, FISP, and FLASH are briefly introduced at the end of the chapter.

1 Gradient Echo Sequence

The gradient echo sequence is the simplest type of MRI sequence. It consists of a series of excitation pulses, each separated by a repetition time TR. Data is acquired at some characteristic time after the application of the excitation pulses and this is defined as the echo time TE. TE is the time between the mid-point of the excitation pulse and the mid-point of the data acquisition as shown in the sequence diagram, figure 5-1 below. The contrast in the image will vary with changes to both TR and TE (see chapter 6).
In terms of k-space representation, the simultaneous application of the phase encode and read dephase gradients results in translation from the centre of k-space from A to B. This is followed by frequency encoding from B to C via the centre of k-space. Each line of data is FT to extract frequency information from the signal and the process is repeated for different phase encode gradient strengths. Figure 5-1 below shows the principle of a gradient echo sequence 1.

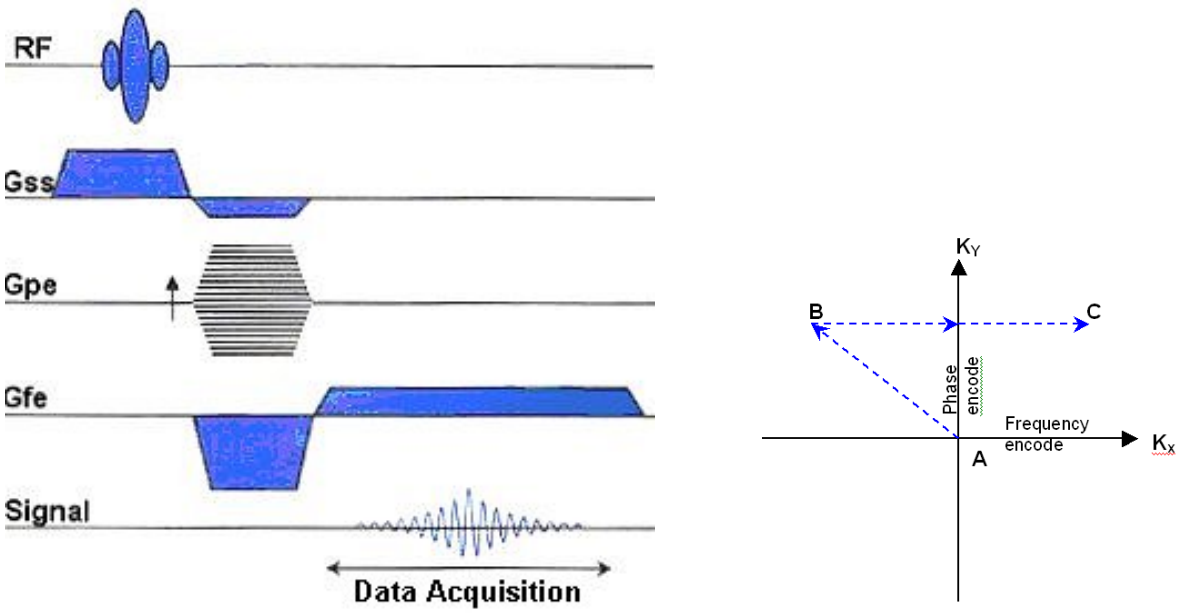


Figure 5- 1: (L) Gradient Echo Sequence and (R) k-space representation
Gradient Echo imaging does not compensate for B0 inhomogeneities. Therefore, there is an increased sensitivity to T2* decay caused by the lack of a 180º refocusing pulse. Gradient Echo sequences have advantages and disadvantages and these are highlighted in

table 5-1 below.

Advantages	Disadvantages
Fast imaging	Difficult to generate good T2 contrast
Low Flip Angle	Sensitive to B0 inhomogeneities
Less RF power	Sensitive to susceptibility effects

Table 5- 1: Advantages and Disadvantages of Gradient Echo Imaging

1 Flip Angle and Ernst Angle

In GE sequences, the choice of flip angle (α) is important for achieving T1-weighted images. GE sequences generally use small flip angles (< 90°) and very short TRs (typically 150 ms) 1. Figure 5-2 below shows that the optimal flip angle depends on the T1 value of the tissue being imaged. A short T1 results in a larger optimal flip angle. The dotted line represents the best contrast-to-noise ratio for marrow, cartilage and bone for a TR of 100 ms.

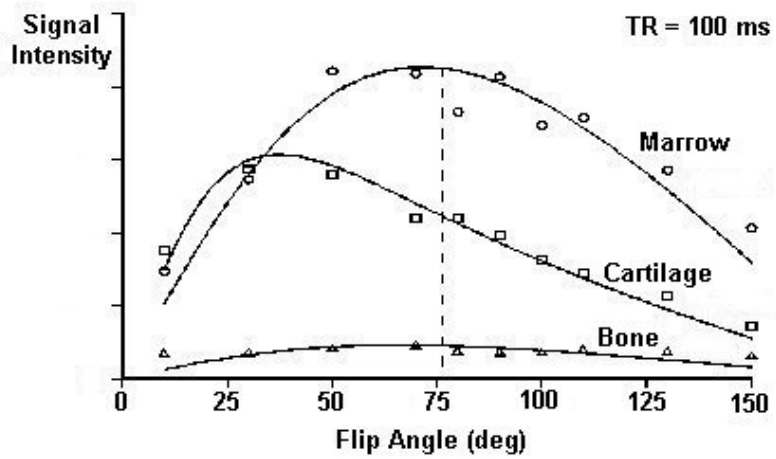


Figure 5- 2: Choice of Flip Angle Determines Optimum Tissue Contrast 2

For each value of T1, there is an optimum flip angle that will give the most signal from a sequence where repeated RF excitations are made. This is known as the Ernst Angle and is given by:

$$\alpha Ernst = \cos^{-1}[\exp(-TR/T1)] \qquad \text{Equation 1}$$

2 Spin Echo Sequence

The spin echo (SE) sequence is similar to the GE sequence with the exception that there is an additional 180° refocusing pulse present. This 180° pulse is exactly halfway between the excitation pulse and the echo (see figure 5-3).

Following a 90° RF pulse, the magnetisation vector lies in the transverse plane. Due to T2* dephasing, some spins slow down and others speed up. A 180° pulse is then applied to 'flip' the spin vectors so that the previously slower vectors are effectively precessing ahead of the previously faster ones. After a further time delay (equal to TE/2), a spin echo is formed, see figure 5-3 below 2.

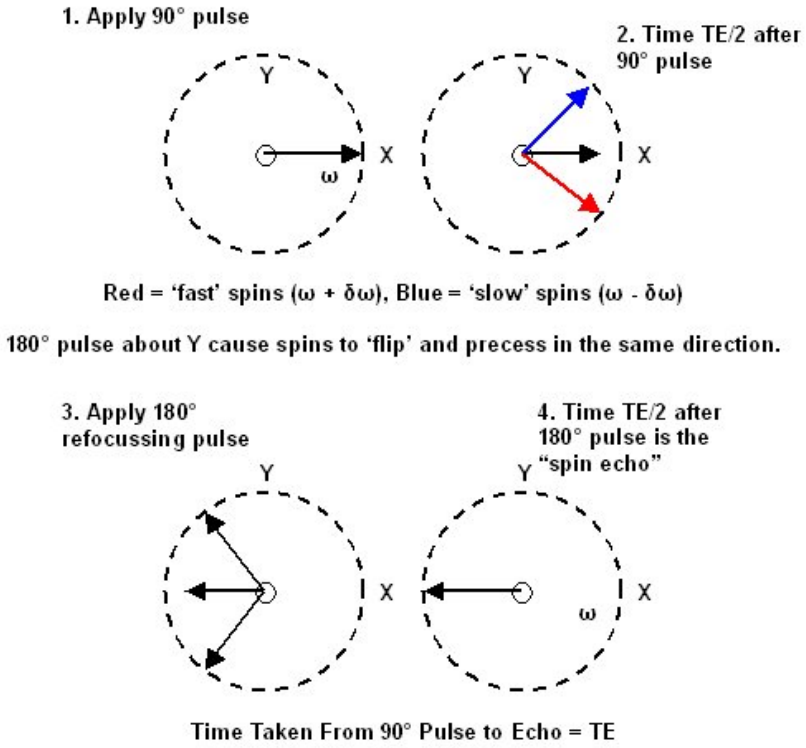


Figure 5- 3: Formation of a Spin Echo

In terms of k-space representation of the spin-echo sequence, the application of phase encoding and read dephase gradients results in movement from the centre of k-space A to position B. The 180º pulse reverses the k-space position in both phase and frequency directions, resulting in movement from B to C. This is followed by frequency encoding from C to D via the centre of k-space (see figure 5-4). Each line of data is Fourier transformed to extract frequency information from the signal and the process is repeated for different phase encode steps. Figure 5-4 below shows a spin echo sequence 1.

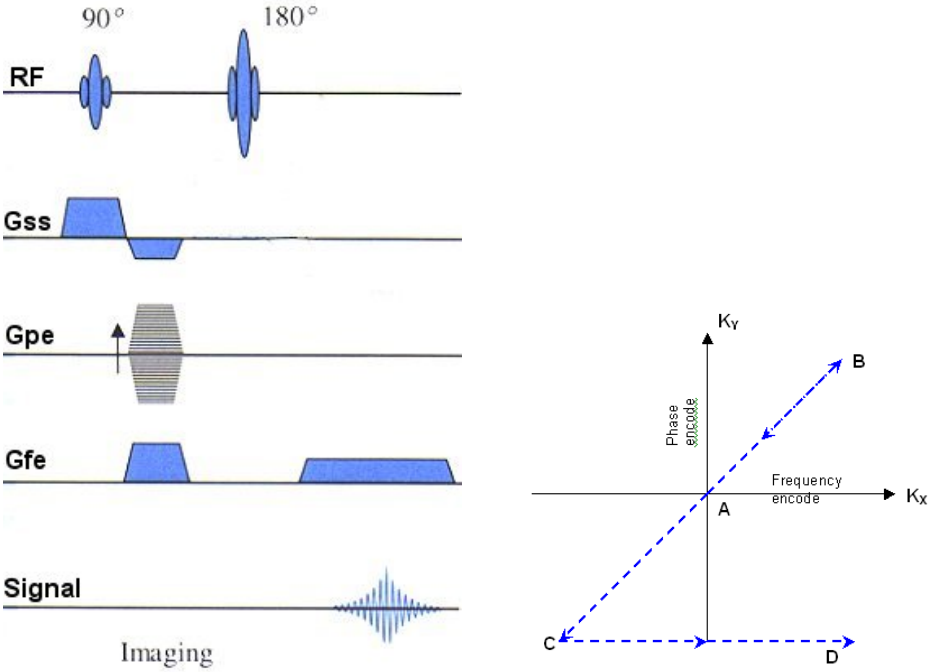


Figure 5- 4: (L) Spin Echo Sequence and (R) k-space representation
The relative advantages and disadvantages of spin echo sequences are shown in table 5-2 below.

Advantages	Disadvantages
High SNR	Long scan times
True T2 weighting	Uses more RF power than a GE sequence
Minimises susceptibility effects	

Table 5- 2: Advantages and Disadvantages of Spin Echo Imaging

3 Inversion Recovery Sequence

Inversion recovery is usually a variant of a SE sequence in that it begins with a 180º inverting pulse. This inverts the longitudinal magnetisation vector through 180º. When the inverting pulse is removed, the magnetisation vector begins to relax back to B0 as shown in figure 5-5 below:

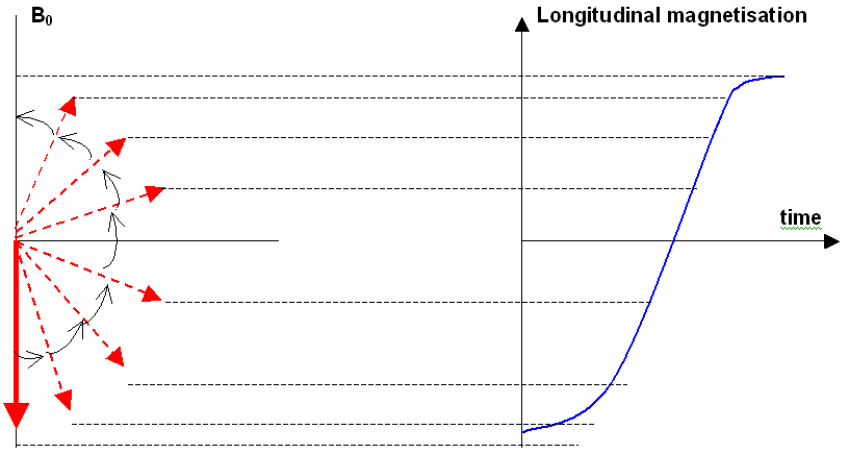


Figure 5- 5: Inversion Recovery

A 90º excitation pulse is then applied after a time from the 180º inverting pulse known as the TI (time to inversion). The contrast of the resultant image depends primarily on the length of the TI as well as the TR and TE. The contrast in the image primarily depends on the magnitude of the longitudinal magnetisation (as in spin echo) following the chosen delay time TI. This is shown in figure 5-6 below.

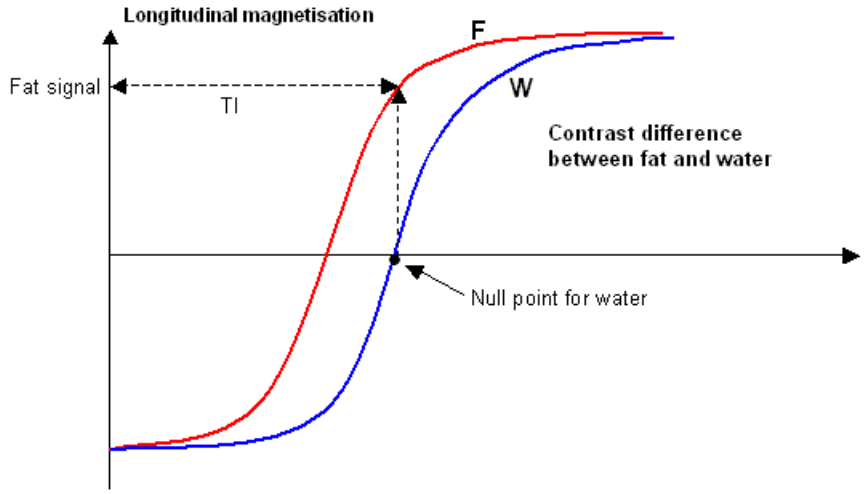


Figure 5- 6: Schematic T1 Weighted Inversion Recovery Diagram for Fat and Water Protons

Figure 5-7 shows the complete inversion recovery pulse sequence.

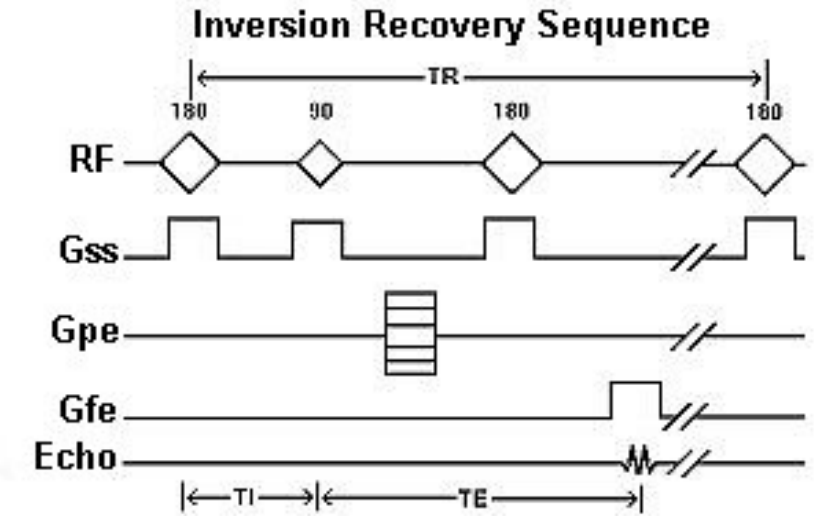


Figure 5- 7: Inversion Recovery Pulse Sequence

1 Uses of Inversion Recovery Sequence

Contrast is based on T1 recovery curves following the 180º inversion pulse. Inversion recovery is used to produce heavily T1 weighted images to demonstrate anatomy. The 180º inverting pulse can produce a large contrast difference between fat and water because full saturation of the fat or water vectors can be achieved by utilising the appropriate TI.

4 STIR (Short TI inversion Recovery)

STIR is an inversion recovery pulse sequence that uses a TI that corresponds to the time it takes fat to recover from full inversion to the transverse plane so that there is no longitudinal magnetisation corresponding to fat. When the 90º excitation pulse is applied after the delay time TI, the signal from fat is nullified. STIR is used to achieve suppression of the fat signal in a T1 weighted image. A TI of 150-175ms achieves fat suppression although this value varies at different field strengths, (140ms for 1.5T scanner). Figure 5-8 below shows that a STIR sequence uses a short TI to suppress the signal from fat in a T2 weighted image.

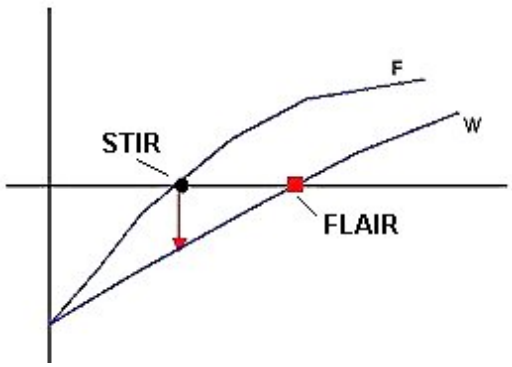


Figure 5- 8: No Fat Vector When the 90° is Applied

5 FLAIR (FLuid Attenuated Inversion Recovery)

FLAIR is another variation of the inversion recovery sequence. In FLAIR, the signal from fluid e.g. cerebrospinal fluid (CSF) is nulled by selecting a TI corresponding to the time of recovery of CSF from 180º inversion to the transverse plane. The signal from CSF is nullified and FLAIR is used to suppress the high CSF signal in T2 and proton density weighted images so that pathology adjacent to the CSF is seen more clearly. A TI of approximately 2000 ms achieves CSF suppression at 1.5T. Figure 5-8 above shows that a FLAIR sequence uses a long TI (eg: 2000 ms) and a short TR (eg: 10 ms) to suppress the signal from water.

6 Fast (Turbo) Spin Echo

Table 5-3 below shows the terms used for Fast Spin Echo sequences by different manufacturers.

Manufacturer	Name
GE	Fast Spin Echo (FSE)
Siemens, Philips	Turbo Spin Echo (TSE)

Table 5- 3: Terms used for Fast Spin Echo by Manufacturer

With each TR in a conventional spin echo, we have a single phase-encoding step. Each of the echoes following each 180º pulse is obtained after a single application of the phase-encoding gradient in conventional spin echo. Each echo has its own k-space, and each time we get an echo, we fill in one line of k-space as shown in figure 5-9 below:

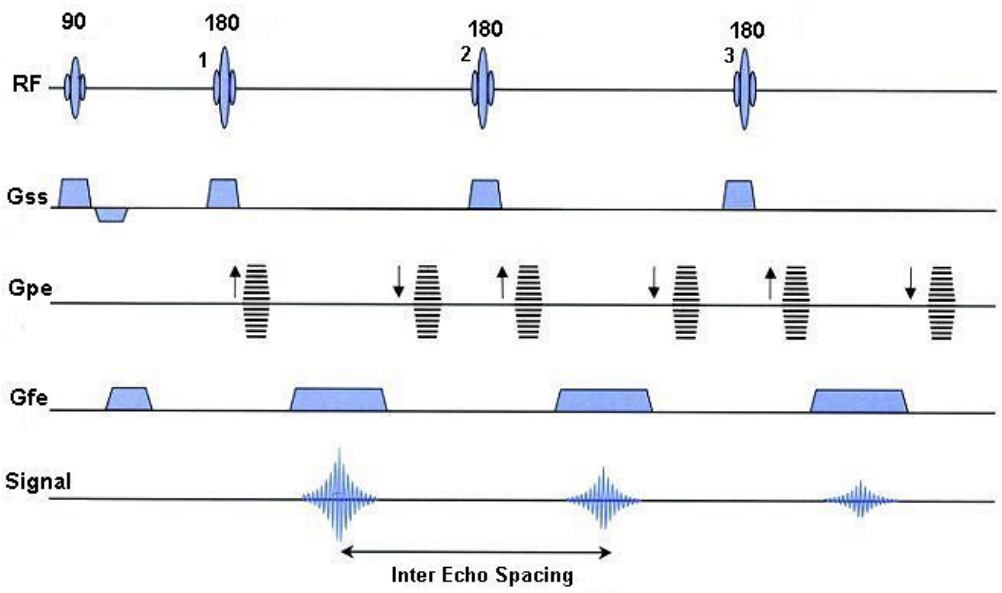


Figure 5- 9: Spin Echo Sequence with 3 Echoes

Fast Spin Echo is a good way of manipulating conventional spin echo to save time. Consider a train of three echoes (Echo Train Length = 3) and only one k-space. This k-space will be filled three lines at a time. Instead of having three separate k-spaces, one for each echo, we will have one k-space using the data from all three echoes as shown in Figure 5-10 below. In conventional spin echo, it took one TR for each line of k-space. Therefore in conventional spin echo, we have to repeat the TR 256 times (for a 256 x 256 matrix). We can therefore cut the time by a factor of three with fast spin echo.

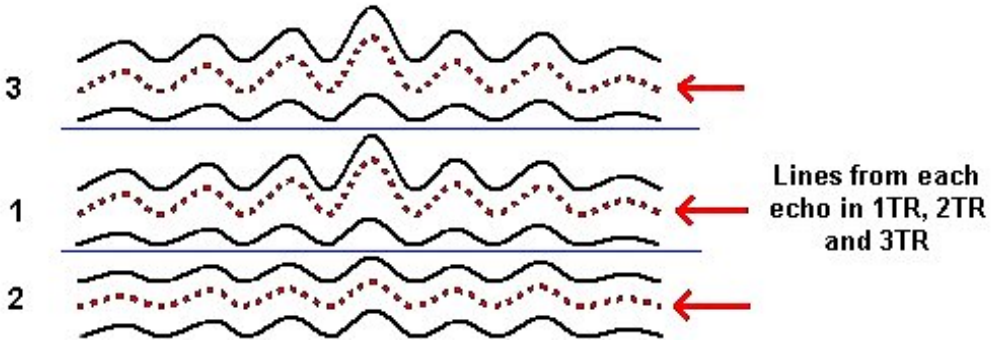


Figure 5- 10: Diagram above shows that in FSE, k-space is filled three lines at a time in one TR, two TR and 3TR. After three TRs, 9 lines of k-space will be filled.

For each TR, we will then fill in another three lines into the single k-space. Because there are a total of 256 lines in k-space, and because during each TR we are filling three lines of k-space, then we only have to repeat the process 86 times, (256 / 3) to fill 256 lines of k-space.
In conventional spin echo, it took one TR for each line of k-space. Therefore in conventional spin echo, we have to repeat the TR 256 times. We can therefore cut the time by a factor of three (for example) with fast spin echo.

1 Advantages of FSE

With FSE, the scan time is decreased (due to faster scanning) and the SNR is maintained because there are still 256 phase-encoding steps. Motion artefacts will be less severe and this technique is better able to cope with poorly shimmed magnetic fields than conventional spin echo.

7 Soft Tissue Contrast in MRI

Contrast is the means by which it is possible to distinguish among soft tissue types owing to differences in observed MRI signal intensities. For example, in musculoskeletal imaging, there are differences among cartilage, bone and synovial fluid. In neuroimaging, there are differences between white and grey matter. The fundamental parameters that affect tissue contrast are the T1 and T2 values, proton density, tissue susceptibility and dynamics. Tissue pathology will also affect contrast, as will the static field strength, the type of sequences used, contrast media and the sequence parameters (TR, TE, TI, FA, SNR etc…).

1 T1 Weighting

To demonstrate T1, proton density or T2 contrast, specific values of TR and TE are selected for a given pulse sequence. The selection of appropriate TR and TE weights an image so that one contrast mechanism predominates over the other two.
A T1 weighted image is one where the contrast depends predominantly on the differences in the T1 times between tissues e.g. fat and water. Because the TR controls how far each vector can recover before it is excited by the next RF pulse, to achieve T1 weighting the TR must be short enough so that neither fat nor water has sufficient time to fully return to B0. If

the TR is too long, both fat and water return to B0 and recover their longitudinal magnetisation fully. When this occurs, T1 relaxation is complete in both tissues and the differences in their T1 times are not demonstrated on the image. The T1 differences between fat and water are shown in figure 5-11 below.

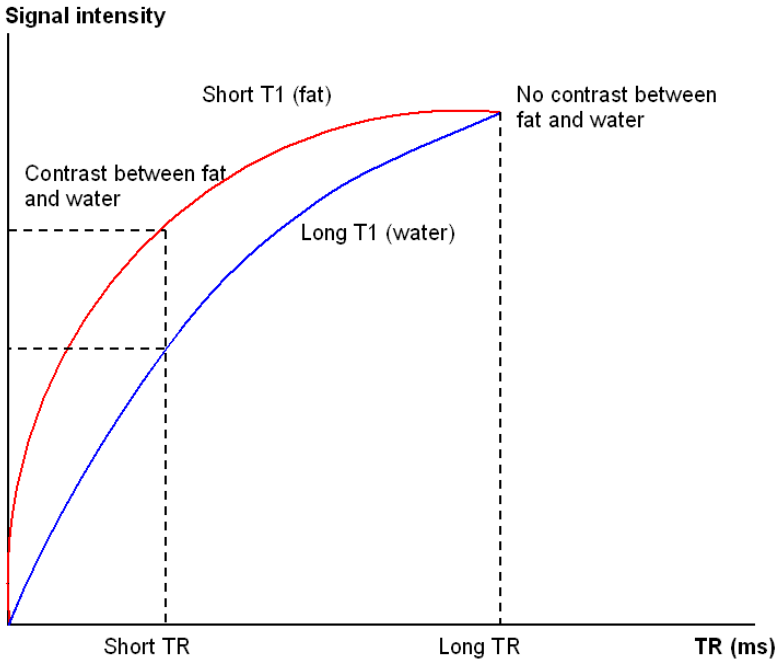


Figure 5- 11: T1 Differences Between Fat and Water

2 T2 Weighting

A T2 weighted image is one where the contrast predominantly depends on the differences in the T2 times between tissues e.g. fat and water. The TE controls the amount of T2 decay that is allowed to occur before the signal is received. To achieve T2 weighting, the TE must be long enough to give both fat and water time to decay. If the TE is too short, neither fat nor water has had time to decay and therefore the differences in their T2 times are not demonstrated in the image. The T2 differences between fat and water are shown in figure 5-12 below.

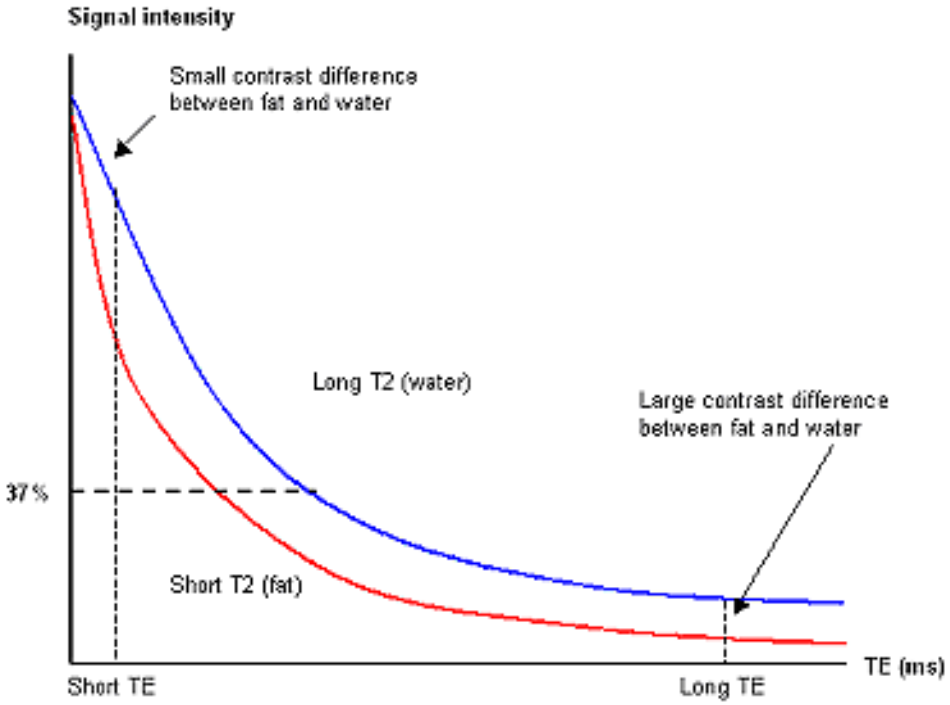
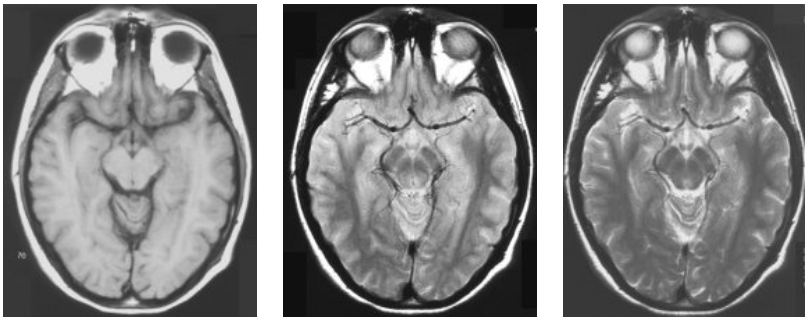


Figure 5- 12: T2 Differences Between Fat and Water

3 Proton Density Weighting

A proton density image is one where the difference in the numbers of protons per unit volume in the patient is the main determining factor in forming image contrast. Proton density weighting is always present to some extent. In order to achieve proton density weighting, the effects of T1 and T2 contrast must be diminished, so that proton density weighting can dominate. A long TR allows tissues e.g. fat and water to fully recover their longitudinal magnetisation and therefore diminishes T1 weighting. A short TE does not give fat or water time to decay and therefore diminishes T2 weighting. Figure 5-13 below shows a comparison of T1, T2 and PD weighting.



T1
PD
T2

Figure 5- 13: T1, PD and T2 Weighted Axial Brain Images

Table 5-4 below compares the TR and TE for T1, T2 and PD weighted sequences.

Weighting	TR	TE
T1	Short	Short
T2	Long	Long
PD	Long	Short

Table 5- 4: Summary of T1, T2 and PD Weighting

4 Contrast to Noise Ratio (CNR)

While improving contrast will generally improve the observer's ability to differentiate tissues, another factor must be considered. When noise levels are substantial compared to the contrast, perceived contrast in reduced. Two images may have identical contrast but different noise levels. The image with the lower CNR will be perceived to have a lower contrast. CNR is defined for tissues A and B as:

$$CNR_{AB} = (S_A - S_B) / Noise \qquad \text{Equation 2}$$

Where SA and SB are signal intensities for tissues A and B.

8 Advanced Gradient Echo Sequences

Table 5-5 below lists some advanced GE sequences. There are three main types of GE sequences. These are listed below along with the names assigned by two different manufacturers.

[1] Free Induction Decay (FID) only (T1 weighted) spoiled Gradient Echo. Sequences of this type are called Fast Low Angle Shot (FLASH) or Spoiled Gradient Recalled Echo (SPGR). These are referred to as 'Spoiled GE' in diagram 5-14 below.
[2] FID and Echo (T1/T2) rewound Gradient Echo. Sequences of this type are called Gradient Recalled Acquisition in the Steady State (GRASS) or Fast Imaging with Steady State Precession (FISP). These are referred to as 'Rewound GE in diagram 5-14.
[3] Echo only (T2) Steady State. Sequences of this type are called 'Steady State Free Precession (SSFP)' or PSIF (FISP reversed).

Sequence Type	GE Systems	SIEMENS
Spoiled GE	SPGR	FLASH
Rewound GE	GRASS	FISP
Echo Only	SSFP	PSIF

Table 5- 5: Advanced Gradient Echo Sequences

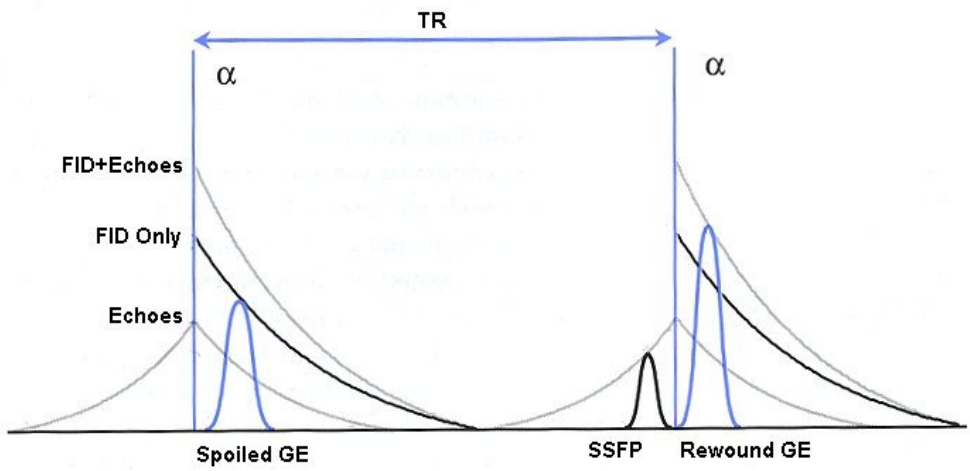


Figure 5- 14: GE: Coherent and Incoherent Signal Formation in the Steady State Resulting from

a Rapid and Regular Train of RF Excitation Pulses 1

1 FLASH or SPGR

The word “spoiling” refers to the elimination of the steady-state transverse magnetisation. There are various ways of doing this, such as by applying RF spoiling, applying variable gradient spoilers and by lengthening TR. By eliminating the steady state component, only the longitudinal component affects the signal in the FLASH technique. This technique lends itself to reduced T2* weighting and increased T1 weighting. This is true provided that α is also large. When α is small, the T1 recovery curves play a minor role and proton density (PD) weighting is increased.

2 FISP (Fast Imaging with Steady-state Precession)

In contrast to spin echo (SE), in gradient echo (GRE) there may be residual transverse magnetisation at the end of each cycle remaining for the next cycle. This residual magnetisation reaches a steady state value after a few cycles. This residual steady state magnetisation (MSS) is added to the transverse magnetisation created by the next α RF pulse and thus increases the length of the vector in the x-y plane. This then yields more T2* weighting. In other words, tissues with a longer T2 have a longer MSS than do tissues with shorter T2. To preserve this steady state component, a “rewinder gradient” is applied in the phase-encoding direction at the end of the cycle to reverse the effects of the phase-encoding gradient applied at the beginning of the cycle.

3 PSIF (REVERSE Fast Imaging with Steady-state Precession)

This technique yields heavily T2 weighted images. Each α pulse contains some 180º pulse embedded in it that acts like a refocusing pulse. This in turn will result in a spin echo at the time of the next α pulse. Hence, contrast is determined by T2 (not T2*). Table 5-6 below shows a comparison of FISP and PSIF sequences.

GE Technique	SNR	CNR	Comments
FISP	Highest	Best possible T2*	Preserves steady-state component
PSIF	Lower	Provides T2W	Gradient recalled SE; TR<TE<2TR

Table 5- 6: Comparison of FISP and PSIF

9 Echo Planar Imaging (EPI)

Single shot EPI requires high performance gradients to allow rapid on and off switching of the gradients. The basic idea is to fill k-space in one shot with readout gradient during one T2* decay or in multiple shots (multishot EPI) by using multiple excitations. Single shot EPI allows oscillating frequency-encoding gradient pulses and complete k-space filling after a single RF pulse. Increased data processing speeds have allowed EPI to become clinically widespread, and it is used in fMRI.

10 3D Gradient Echo for Volumes

3D imaging with contiguous thin slices is feasible by using GE techniques. This type of imaging is accomplished by addition of a phase-encoding step (NZ) in the slice-select direction (z-axis).

Total scan time = TR x NY x NEX x NZ

Where NZ is the number of phase encoding steps in the z-direction. NZ is usually a power of 2 (32, 64, 128 etc). This provides a slab of slices.
An extremely short TR makes it possible to do 3D imaging in a reasonable time.
For example, the scan time for a 3D GRE technique in the cervical spine with the following parameters: TR = 30, TE = 13, Angle = 5º, NEX = 1, NY = 256 x 192, NZ = 64.
Scan time = (TR)(NEX)(NY)(NZ) = (30)(1)(192)(32) = 184320 ms = 3 min 4 sec.
The advantages of 3D GE include rapid volume imaging of thin contiguous slices without crosstalk and increased SNR, because SNR α (NZ)½

11 Fat Suppression

Hydrogen atoms in fat have a lower Larmor frequency than those in water and this difference is called the chemical shift. It is approximately 3.5 ppm and is independent of the magnetic field strength 1. In order to improve fat/water soft-tissue contrast it is often useful to 'null' the signal from the fat ('fat suppression'). One method is to use a STIR (Short Tau Inversion Recovery) sequence. In this sequence, a 180° pulse is applied to invert the longitudinal magnetisation, and after a period TI (the Inversion Time), a conventional gradient-echo sequence is implemented.
MRI allows the suppression of the signal coming from fat. This suppression allows perturbation of tissue contrast to enhance the signal coming from tissues of greater interest. Two types of tissue are commonly suppressed in clinical practice: FAT and WATER. Suppression can be achieved by inversion recovery techniques, chemical saturation or frequency-selective pre-saturation and spatial pre-saturation in the FoV.

1 Clinical Applications of FATSAT

FATSAT is used to minimise the signal from fat, relative to surrounding tissues. In musculoskeletal applications it is used to minimise the fat signal in the marrow emphasising the signal from marrow oedema (due to bone contusion, tumour, infection etc.). When used for the eye orbits it suppresses the retro-orbital fat to allow detection of an enhancing retro-orbital pathology on a contrast-enhanced study. FATSAT applied to the neck suppresses fat in order to detect and better evaluate the extent of a mass. FATSAT is actually used in many other clinical applications, such as body MRI (liver, kidney imaging) and breast MRI to name a few examples.

12 Summary

This chapter on MRI sequences described the basic gradient echo and spin echo sequences as well as inversion recovery. The relation between the flip angle, the Ernst angle and tissue contrast was explained. Other soft tissue contrast factors such as T1, T2 and PD weighting were addressed along with the contrast-to-noise ratio. Finally, an overview of advanced gradient echo sequences was provided. These were divided into three classes and qualitatively described.

13 References

[1] D. W. McRobbie, E. A. Moore, M. J. Graves, M. R. Prince. MRI – From Picture to Proton (2003).
Cambridge University Press.

[2] Gandy. S. MRI Physics Lecture Series (2004). Soft Tissue Contrast in MRI. Ninewells Hospital,
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