Module 5
Sequences and applications II

After reading this module, you will:

- Be able to differentiate between a spin echo and a gradient echo sequence and understand their respective advantages and disadvantages.
- Be familiar with the parameters and their adaptation to generate various image weightings.
- Be familiar with the purpose of the Inversion Recovery Stimulus

5.1 The gradient echo

The type of sequence	Philips	Siemens	GE	Hitachi	Toshiba
The gradient echo	FFE	GRE	GRE	GE	FE

Two significant points differentiate the gradient echo sequences and the SE sequences. The stimulus pulse, identified with the flip angle (90° with a "classic" SE) is usually selected as lower than 90°.

There is no 180° pulse to force rephasing and thus the echo. Instead, the direction of the frequency encoding gradient (switched upon reading out the echo) is reversed.

A flip angle under 90° reduces the magnitude of the magnetization flipped in the transverse level and thus contributing to the signal. Nevertheless, the longitudinal magnetization also returns to the ground state much faster. This means the need to use significantly shorter TR times, thus saving examination time.

The disadvantage of the GE sequence involves an effect so far neglected: the interactions of the spins cause the transverse magnetization to relax, but so do irregularities in the static magnetic field and the gradients.

If the gradients and static field are not altered, these irregularities become stationary. This is also the case with the SE sequences: after the 180° pulse, the spins rotate in an opposite direction. This means that they are subject to the same perturbation as before but present a reverse movement sign; the influences largely cancel each other out.

As soon as the echo is generated by a reversal of the gradients (hence the name gradient echo) the perturbation also changes upon the change in direction of the spin, thus producing a further perturbation.

Thus, we say that GE images are T_2* weighted. The exterior disruption is included in the "*". This not only shortens the actual T_2 times, but makes the GE sequences more prone to susceptibility artefacts in the images.

5.1.1 The spoiled gradient echo

The type of sequence	Philips	Siemens	GE	Hitachi	Toshiba
Spoiled GE	T1-FFE	FLASH	SPGR	RSSG	RF-spoiled FE

The GE sequences were principally developed to generate images faster than those produced with SE techniques. As a rule, the TR is so short that the transverse magnetization is not always entirely relaxed when the next stimulus pulse is projected.

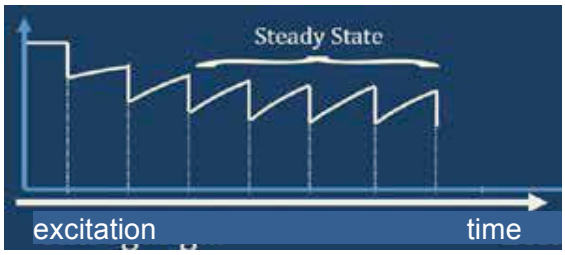
Two approaches have been developed to meet this problem in a clinical setting.

One uses "spoiler gradients." This involves the destruction of the residual magnetization after every pulse via the switching of an additional gradient known as a spoiler gradient (sGE) with an arbitrary phase length.

Introduced by Siemens in 1985 as a Fast Low Angle Shot (FLASH) it enabled fast recording of T_1- and ρ-weighted MR images.

5.1.2 The steady state gradient echo

The type of sequence	Philips	Siemens	GE	Hitachi	Toshiba
SSFP	FFE	FISP	MPGR	TRSG	FE
bSSFP	Balanced FFE	True FISP	FIESTA	BASG	True SSFP



The rapid generation of T_2-weighted images was still not possible. It was eventually achieved by the highly complex Steady State Technique, generally known as "Steady-State Free Precession" (SSFP).

To this end, excitation pulses are projected in quick succession until the magnetization has become balanced. The spins relax between every stimulus, but only to the same extent that they are deflected by the following stimulus. This generates a dynamic balance or "steady state." A complicated gradient inversion (not described here) enables the weighting of the images at a ratio of T_1 to T_2*.

At the time of the invention of this imaging method, the scanners were not yet sufficiently developed to implement the complex gradient switching as planned. Siemens initially introduced the methods as "Fast Imaging with Steady Precession (FISP)."

The advent of the new scanner generation enabled the implementation of "balanced SSFP" in its original form. This became known as the only true FISP (True FISP), a name which Siemens still uses today.

5.1.3 Ultrafast SE / GE

The type of sequence	Philips	Siemens	GE	Hitachi	Toshiba
Ultrafast SE	Ssh	HASTE	SS-FSE	FSE-ADA	FASE
Ultrafast GE	THRIVE	VIBE	LAVA	SARGE	RADIANCE

The k-space is structured symmetrically around its centre. Theoretically, it is necessary to scan only half of the information. The rest can be mirrored.

In practice, the incidence of a number of random perturbances means that to do so would double their incidence thus reducing the image quality. Nevertheless, partial scanning can produce good results, especially in the scanning of the abdomen (usually 2/3 or 3/4 of the space) as entire imaging volumes can be scanned within one or two breath-holding phases. The ultra-fast sequences also use the acceleration technique familiar from FSE in order to achieve shorter acquisition times.

5.2 Echo planar imaging

The type of sequence	Philips	Siemens	GE	Hitachi	Toshiba
EPI	EPI	EPI	EPI	EPI	EPI

The EPI method (Echo Planar Imaging) is a special approach to scanning the k-space. Rather than proceeding row for row from a single direction, it employs highly-complex gradient switchings to record the signal in a meandering pattern.

Using the "single-shot technique," it scans an entire k-space after only a single stimulus. The number of gradient echoes is used to calculate the EPI factor. The rapid T2* decline means that only some 100 ms remain after the stimulus in which to generate the echo.

As a result, the read-out is generally restricted to between 64 and 128 echoes (corresponds to a 64 / 128 matrix). With a large FOV, this produces a poor spatial resolution; small FOVs (a better resolution) can lead to interfolding. The speed with which the images are gathered means that they are mostly free of all motion artefacts.

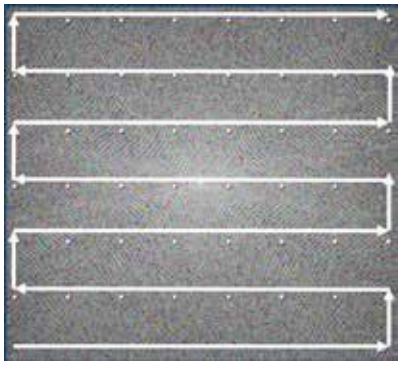
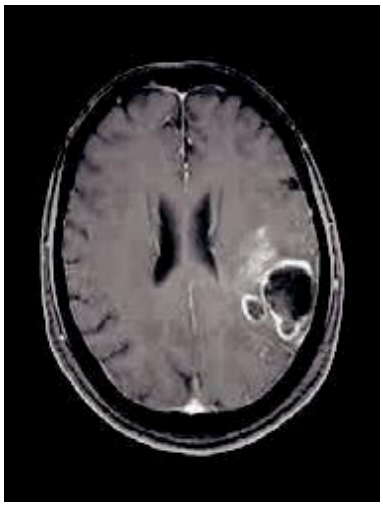


Figure 5.2
A meander-form k-space Scanning in EPI

As a result, EPI is suited to the investigation of dynamic procedures (cardio imaging) and diffusion-weighted imaging. The constant switching of the gradients to scan in a single sweep is prone to susceptibility artefacts.

5.3 Contrast agent-enhanced imaging



Extracellular contrast agents are based on gadolinium atoms bonded to other atoms in a number of ways (e.g. Gd-BT-DO3A, Gd-DTPA, Gd-EOB-DTPA). The magnetic susceptibility of gadolinium mean that these bonds are used to shorten the T_1 time.

A magnetic reaction between the hydrogen spins and the gadolinium atoms in the contrast agent of the T_1 relaxationis subject to considerable acceleration. As a result, tissue enriched with the contrast agent appears light in T_1-weighted sequences.

As malignant tissue alterations often present increased micro-vascularization, contrast-enhanced (CE) imaging can provide information about the micro-circulation of the blood through the capillary structure of the tissue. Perfusion (defined as a quantifiable quantity) is the term used for the blood volume ΔV, which flows through the biological tissue of the mass per unit of time Δt.

Figure 5.3:
CA-assisted imaging of the brain

Hypervasculated tissue should exhibit a higher level of perfusion and the contrast agent should both accumulate locally but also be washed out more quickly.

Dynamic imaging gathers a reference data set with the same imaging parameters as in the later dynamic sequences. Contrast agent is applied intravenously with a high and constant bolus. This is followed by the accumulation of the dynamic contrast agent and the subsequent washout behaviour. Conventional liver protocols usually use VIBE / THRIVE / LAVA sequences (3D volume acquisition with slice interpolation and breath-hold techniques) to record the arterial, portal venous, venous and late phase.

5.4 Diffusion-weighted imaging

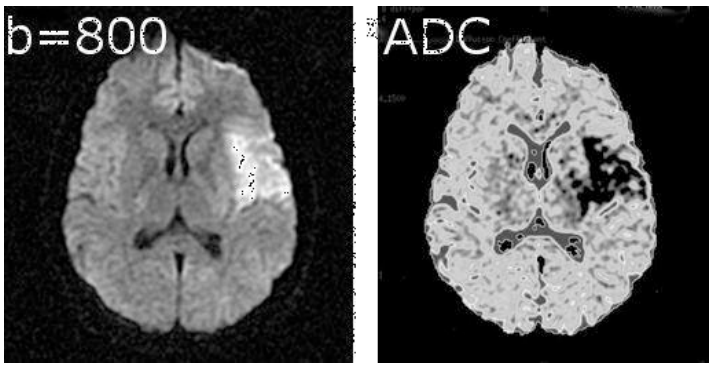


Figure 5.4:
Disrupted diffusion gives an ischemic lesion a light appearance: the random spin movements in the extracellular tissue have declined in comparison to the surroundings. ADC depiction indicates the middle free movement of the spins in the level (mm^2/s). The ischemic areal presents reduced diffusion.

Diffusion imaging reveals the movements of water molecules in the intra and extra-cellular space. In normal tissue, this random motion is usually relatively distinctive. In tumours on the other hand, the alterations in the tissue, the reconstruction of cell membranes and a compacted cell structure often restricts this movement. In addition to its increasing significance in the diagnosis of tumours, diffusion-weighted imaging is also used in the diagnosis of strokes.

Large amounts of parts of the extracellular water is displaced in the intracellular space immediately after the ischemic event. Moreover, the molecules here can move less freely.

This "only needs" to be depicted:
Diffusion-weighting works on the basis of the switching of gradients before and after the 180° rephasing pulse of an SE-EPI. This is comparable with the normal procedure of phase encoding. The gradients before and after the pulse accelerate the dephasing and rephasing of the spins. If they remain in the same spatial position (after complete rephasing) they will issue a clear signal at the TE time. Movement of the spins in the meantime means insufficient rephasing. This in turn results in a reduced signal and a locally-occurring hypointense areal. Whilst the influence of motion effects is deleterious to normal imaging, it is encouraged in diffusion-weighted imaging through the especially strong gradients before and after the inversion pulse.

Diffusion imaging is a method used to record and depict errors in the phase encoding. The challenge presented by diffusion imaging is the imaging of the "correct" perturbance with an acceptable spatial resolution. Fitting a slow imaging sequence with the necessary diffusion gradient would result in the dominance of signal losses from macroscopic movements such as blood pulsation in the vessels.

The sequence must be run quickly in order to depict just the fast movement processes. At present, SE EPI sequences are suitable for this purpose.

The intensity of the spin echo thus generated depends on the diffusion of the extracellular water. To avoid the necessity of setting the strength, form and duration of the diffusion gradients individually, these parameters are aligned together through the so-called b-factor, the value of which is specified in seconds per square millimetre.

The following applies:
Diffusion-weighting increases with the size of the b-factor. Typical b-values lie between 0 and 1500 s/mm^2. Usually, multiple values are used consecutively. The rapid imaging means relatively low spatial resolution and complicates recognition of the anatomic landmarks.

A minimum of two b-values enables the calculation of an Apparent Diffusion Coefficient (ADC).

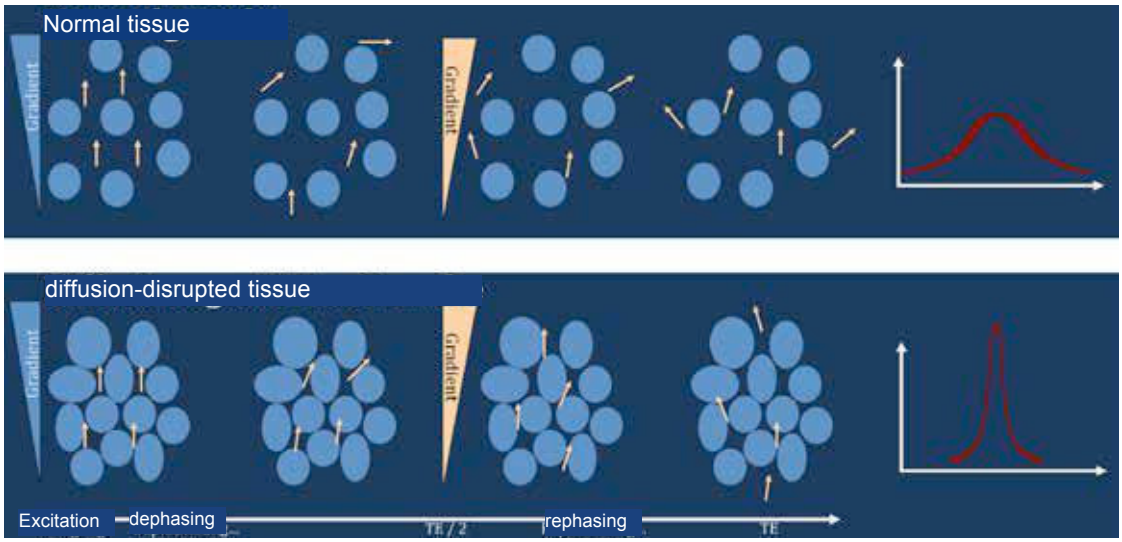
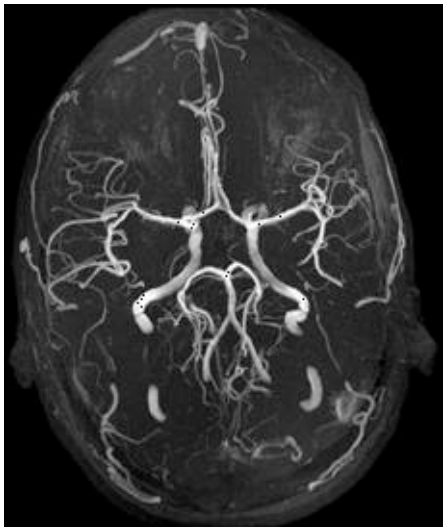


Figure 5.5:
In normal tissue with conventional diffusion characteristics, the spins move so strongly up to the TE time through random movement that proper rephasing cannot occur. The spins in diffusion-disrupted tissue remain in their starting position, rephase better and provide a clearer echo signal.

5.5 Magnetic resonance angiography

After reading this section, you will:

- Understand the flow phenomena found in MRI.
- Be familiar with contrast-enhanced magnetic resonance angiography and its differences in comparison with the Time of Flight procedure.



As with every other motion with which the MRI device is unfamiliar, blood flow presents a problem: the spatial encoding of the images is falsified through the gradients. This results in the development of artefacts in the reconstructed images. They usually run along the direction of phase encoding and are represented as ghost images in the vessels through which the blood flows.

Whilst the placement of saturators or a good choice of phase encoding direction can keep these developments from the area involved in the diagnosis, angiography (which does not use contrast agents) uses this effect to locate vessels. We differentiate between two types of imaging in magnetic resonance angiography which use the motion of the spins.

- Time-of-Flight Angiography (TOF), also known as Inflow.
- Phase Contrast Angiography.

We will focus on the TOF technique.

The development of modern contrast agents and faster scanner technology means an increased role for CE angiography.

A number of methods effect a reduction in disruptive background signal.

Whichever technique is used to depict the vessels, a strategy is required with which to suppress the stationary tissue. It can be advantageous to use 2D measurement instead of a 3D measurement, although this also results in lower-quality maximum intensity projections (MIPs).

Angio techniques without contrast agents assume an equal speed and direction of blood flow throughout the volume without turbulence. As this is rarely the case, its absence often causes artefacts.

The success of a CE angiography depends on the correct timing. The bolus must be located in the arteries to be examined during measurement of the central k-space section.

5.5.1 TOF – Time-of-Flight Angiography

Time-of-Flight Angiography uses the blood itself as a contrast agent. The design of the sequence means that the flowing blood emits a stronger signal than the surrounding tissue. A very short TR is used to this end.

This time is set so short so that the stimulated spins can only partially straighten.

The next stimulus pulse flips this incompletely-recovered longitudinal magnetization again, by the flip angle. This weak longitudinal magnetization has insufficient time to recover before being deflected again by the flip angle. After a few stimuli, a state has been reached in which the magnetization recovers only to the magnitude where it can be deflected again.

This is named the steady state. Sometimes, it results in the stationary tissue being depicted dark.

If new spins were to flow into the volume, as they have yet to reach a steady state, they will be flipped out of their full longitudinal magnetization. The longitudinal magnetization of the blood spins available is considerably higher than the signal of the stationary tissues in its steady state.

The signal strength which the blood spins are able to emit depends on:

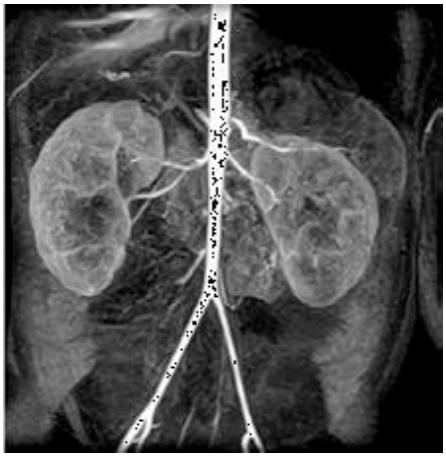
- The flow rate (as high as possible to permit faster exchange of the flowing spins with new, still unstimulated spins).
- The orientation of the vessel examined (as perpendicular to the slice as possible). If the vessel runs in the slice, the blood spins will also reach the steady state.
- Sequence parameters TR (as short as possible in order to reach the steady state quickly), the flip angle (high), TE and the slice thickness.

The TOF always encounters problems if the flow in the vessel is very slow or if turbulence develops (e.g. behind stenosis). A further problem is the course of the vessel in the slice which cannot always be avoided (e.g. the A cerebri media) as the blood can also then reach the steady state.

If the surrounding tissue has a very short T1 time, it is possible that it is depicted light despite the short TR time, as it is able to relax sufficiently. This is a considerable problem when presented with a high proportion of fat, the presence of a haematoma or thrombosis as the latter emits as strong a signal as the flowing blood. The slow flow of blood in the veins and the large sinus means that it can be expedient to measure a venous TOF using a 2D technique.

The unscanned vascular system (venous or arterial) can be saturated using a saturator.

5.6 Contrast-enhanced magnetic resonance angiography



CE MRA depicts blood flow as light on a dark surrounding (the bright-blood technique). In contrast to TOF (inflow angiography) which uses the blood itself as a contrast agent, the source of the signal increase is the intravenous injection of a contrast agent.

This effects a considerable reduction in the T1 time of the contrast agent - blood admixture. As a result, the short TR time (up to 5ms depending on the device) is sufficiently relaxed and able to emit a signal.

This produces a whole range of advantages: The vascular signal is largely independent of saturation effects. This means that angio volumes can be planned based entirely on the anatomic situation. Nothing further must be taken into account.

Figure 5.7:
CE angiography

CE angiography produces reliable and robust images of aneurysms, dissections and congenital anomalies which cannot be depicted well by other procedures due to their unfavourable positioning (e.g. the course of the vessel in the slice). In contrast to the TOF (inflow) technique, even turbulent flows (as those which can develop after stenosis) present no problem. Nevertheless, they do not provide any information regarding the direction of the blood flow. Modern scanners also provide high volume coverage which can also be used in the breath-holding technique.

5.6.1 CINE-MRA

A combination of various acceleration techniques and intelligent k-space read-out and division also permits a 4D-MRA. The fourth dimension is that of time. The result is a dynamic depiction of the various enrichment phases.

Different manufacturers have all named these techniques differently, but they all use a division of the k-space.

Siemens: TWIST
Division of the k-space into contrast-providing central sections (region A) and resolution information (region B, which is itself subdivided). A section of region B is measured after every measurement of the central region A, after which, region A is measured again. Following information capture from region A, the neighbouring information from region B is gathered so that a complete data set is produced.

Philips: 4D-TRAK
The periphery of the k-space is measured with the information about the resolution. The central k -space proportion (determining the image contrast) is then measured repeatedly. The resolution information is loaned for every phase of the reference measurement - hence the name "view sharing".

GE: TRICKS

The principle is very similar to the TWIST principle. The k-space is divided and various areas are readout subsequently and in turn. The centre is subject to considerably more frequent measurement. The temporally neighbouring sections are combined for reconstruction purposes so that a completely filled k-space is available.

This generates sequences with considerably-reduced acquisition times (down to a few seconds) thus enabling sufficient temporal resolution for dynamic imaging. The first images - even before the application of contrast agent - are used as a reference and serve as a subtraction mask.

The challenges experienced during these sequences are the high demands placed on the scanner hardware (image calculation, fast gradient switching and short excitation pulse sequences).

Injection-synchronization

The contrast enhanced sequences require the exact timing of the contrast bolus and acquisition in order to guarantee that the intravascular passage of the contrast agent is recorded correctly. If the imaging is performed too late, the contrast has already entered the venous phase. The triggering can be effected via a test bolus or real time tracking of the bolus (real-time MRI implemented as a care bolus / bolus track / fluoro trigger).

The application of contrast agent should be performed with a somewhat higher injection rate than with normal imaging as the T1 reduction to be achieved depends not just on the relaxivity of the contrast agent, but also the local concentration (the number of contrast molecules present).

It is important that the arteries contain a high concentration of highly-effective contrast agent molecules when reading out the image contrast.