Gary Liney

MRI from A to Z

A Definitive Guide for Medical Professionals

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From 'AB systems' to 'Zipper artefact' – even for the experienced practitioner in MRI, the plethora of technical terms and acronyms can be daunting and bewildering. This concise but comprehensive guide provides an effective and practical introduction to the full range of this terminology. It will be an invaluable source of reference for all students, trainees and medical professionals working with MRI. More than 800 terms commonly encountered in MR imaging and spectroscopy are clearly defined, explained and cross-referenced. Illustrations are used to enhance and explain many of the definitions, and references point the reader to more in-depth coverage. As well as being a compendium of terms from A to Z, the volume concludes with a useful collection of appendices, which tabulate many of the key constants, properties and equations of relevance.

Dr Gary Liney is a respected MR physicist who has worked for many years in the field of MR imaging and spectroscopy at both a clinical and academic level. His work has been published in numerous peer-reviewed journals and presented at many international conferences.

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A Definitive Guide for Medical Professionals

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For David, Rebecca and Matthew

Children are a poor man's riches (*English proverb*)

Contents

Preface

What does FIESTA stand for?
What's a bounce point artefact?
What's the equation for a stimulated echo?

This book will be an invaluable source of reference for anyone working in the field of magnetic resonance, from the novice academic student to the experienced medical professional.

The book brings together more than 800 terms of reference in common usage in the diverse field of MR imaging and spectroscopy. Explanations are amplified with equations, examples and figures, and further references are provided. While every effort has been made to correctly assign or identify manufacturer-specific terms as appropriate, inevitably there will be some cross-over. If you can think of anything I have missed out, please get in touch and help make the next edition even better!

Thanks to colleagues at the Centre for MRI Investigations (CMRI), Hull Royal Infirmary, and in particular Roberto Garcia-Alvarez and Martin Pickles for proofreading and helpful suggestions.

The front cover shows the author performing an auditory fMRI experiment and has been processed by Roberto Garcia-Alvarez.

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Main glossary

Aa

AB systems

Referring to molecules exhibiting multiply split MRS peaks due to spin-spin interactions. In an AB system, the chemical shift between the spins is of similar magnitude to the splitting constant (J). A common example is citrate (abundant in the normal prostate). Citrate consists of two pairs of methylene protons (A and B, see Appendix VI) that are strongly coupled such that:

$$\nu_A - \nu_B = 0.5\,J$$

where ν_A, ν_B are the resonating frequencies of the two protons. A tall central doublet is split into two smaller peaks either side, which are not usually resolved in vivo at 1.5 tesla. Citrate exhibits strong echo modulation.

See also J-coupling and AX systems.

Reference R. B. Mulkern & J. L. Bowers (1994). Density matrix calculations of AB spectra from multipulse sequences: quantum mechanics meets spectroscopy. *Concepts Magn. Reson.* **6**, 1–23.

Absolute peak area quantification

MR spectroscopy method of using peak area ratios where the denominator is the water peak. The areas are adjusted for differences in relaxation times, and the actual concentration of the metabolite is determined from:

$$[m] = [w] \times \frac{2}{n} \times \frac{S_0^m}{S_0^w}$$

where $[w]$ is the concentration of water and S_0 are the peak area amplitudes of the metabolite and water signals at equilibrium, i.e. having been corrected for relaxation, which has occurred at the finite time of measurement. The factor $2/n$ corrects for the number of protons contributing to the signal (here 2 is for water).

Note: $[w]$ is taken as 55.55 Mol/kg.

Reference P. B. Barker, B. J. Soher, S. J. Blackband, J. C. Chatham, V. P. Mathews & R. N. Bryan (1993). Quantitation of proton NMR spectra of the human brain using tissue water as an internal concentration reference. *NMR Biomed.* **6**, 89–94.

Acoustic noise

The audible noise produced by the scanner. Caused by vibrations in the gradient coils induced by the rapidly oscillating currents passing through them in the presence of the main magnetic field. Ear protection must by worn by patients because of this noise. Gradient-intensive sequences, e.g. 3-D GRE, EPI, produce the highest noise levels. Typically, the recorded noise level may be weighted (dB (A) scale) to account for the frequency response of the human ear. Values of 115 dB (A) have been recorded with EPI. The Lorentz force, and therefore noise level, increases with field strength (typically a 6 dB increase from 1.5 to 3.0 tesla). Current methods to combat noise include mounting the gradient coils to the floor to reduce vibrations and lining the bore with a vacuum. More sophisticated measures include active noise reduction.

See also bore liner and vacuum bore.

Reference F. G. Shellock, M. Ziarati, D. Atkinson & D. Y. Chen (1998). Determination of gradient magnetic field-induced acoustic noise associated with the use of echoplanar and three-dimensional fast spin echo techniques. *J. Magn. Reson. Imag.* **8**, 1154.

Acquisition time

Time taken to acquire an MR image. For a spin-echo sequence it is given by:

$$N_p \times N_A \times TR$$

where N_p is the number of phase encoding steps, N_A is the number of signal averages, and TR is the repetition time. Shorter scan times means a trade-off in image quality in terms of resolution (N_p), SNR (N_A) and contrast (TR). Scan times may also be reduced by using parallel imaging.

In gradient-echo sequences with very short TR times, the above equation includes a factor for the number of slices acquired.

Active noise reduction

Advanced method of reducing gradient noise produced from the scanner. Utilises force-balanced coils, which are designed so that the Lorentz forces act in a symmetrical manner to counteract the vibrations. May offer up to 30 dB improvement.

See also acoustic noise.

Reference R. W. Bowtell & P. M. Mansfield (1995). Quiet transverse gradient coils: Lorentz force balancing designs using geometric similitude. *Magn. Reson. Med.* **34**, 494.

Active shielding

Refers to either shielding of the main magnetic field or the gradient coils. The fringe field may be actively shielded using an additional set of coil windings around the main set, with a current of opposite polarity passing through it. An unshielded 7 tesla scanner has a 5 gauss fringe field of 23 m.

See also passive shielding.

Actively shielded gradients are now standard on all systems. This reduces eddy currents in the cryogen and other conducting structures.

Active shimming

Improving the homogeneity of the main magnetic field (the shim) by passing current through additional sets of coils within the scanner to augment the field. Typically, 12 to 18 sets of coils are used which affect the field in each orthogonal direction. A first-order shim changes the field in a linear fashion, a second-order shim produces field changes that vary with the square of distance and so on (higher-order shims). The shim coils themselves may be resistive or superconducting.

See also passive shimming.

ADC

Apparent diffusion coefficient. Refers to the measurable value of diffusion rather than the actual value due to the effects of cell boundaries, etc. The signal attenuation observed in a diffusion-weighted image due to the apparent diffusion coefficient, D, is:

$$S = S_0 . \exp(-b D)$$

where b is the gradient factor (see *b*-factor).

The ADC value for water is approximately 2.0×10^{-3} mm^2 s^{-1}.

Not to be confused with the analogue-to-digital converter (ADC) which digitises the measured MR signal before further processing.

Reference B. Issa (2002). In vivo measurement of the apparent diffusion coefficient in normal and malignant prostatic tissues using echo-planar imaging. *J. Magn. Reson. Imag.*, **16**, 196–200.

ADC map

A parameter map in which the pixel intensity is equal to the value of ADC. The map may be obtained from images acquired at several different values of *b*-factor. Care must be taken in selecting a minimum *b* value as flow effects dominate at very low *b*. Alternatively, a two-point method may be used typically acquiring a $b = 0$ image and a second image at a high *b* value. ADC maps have proved useful in diagnosing stroke but do not provide any directional information.

See also *DTI*.

Adiabatic pulse

Specific use of a variable frequency excitation pulse which is swept through the Larmor frequency. These pulses are less sensitive to B_1 inhomogeneities than conventional pulses but take longer to apply. Used in continuous wave NMR.

Agarose gel

Common material used in the construction of phantoms. Its T_2 relaxivity (10 $mM^{-1}\ s^{-1}$) is much higher than corresponding values for T_1 (0.05 $mM^{-1}\ s^{-1}$), which means T_2 values can be made to vary considerably with little alteration in T_1. The material is often mixed with Gd-DTPA to produce phantoms with a range of T_1 and T_2 values.

See also gel phantom.

Reference M. D. Mitchell, H. L. Kundell, L. Zxel & P. M. Joseph. (1986). Agarose as a tissue equivalent phantom material for NMR imaging. *Magn. Reson. Imag.*, **4**, 263–266.

AIF

Arterial input function. This is the signal-time characteristic of the contrast agent bolus in the blood, and may be used to model uptake in other tissues. For best results, an artery near to the site of interest needs to be selected for the appropriate AIF. This function can be deconvolved from tissue or tumour enhancement to quantitate perfusion.

See also dynamic scanning and perfusion imaging.

Alanine

Proton spectroscopy peak with a resonance at 1.48 ppm. It is often seen to increase in meningiomas.

Aliasing

Image artefact caused by anatomy extending beyond the imaging field of view but within the sensitive volume of the RF

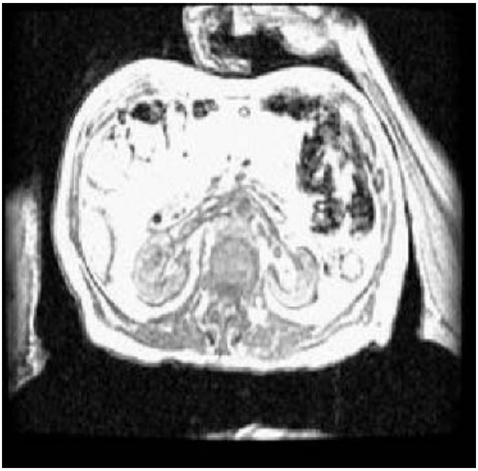


Figure 1. Phase wrap or **aliasing** results in the top of the hand appearing at the bottom of this image.

coil. It results in the offending part of the anatomy being incorrectly mis-mapped onto the opposite side of the image. Frequency oversampling usually ensures aliasing is only possible in the phase direction and can be avoided by swapping the direction of encoding. It is also referred to as wrap and foldover.

See also no phase wrap, frequency wrap and nyquist frequency.

Alignment

Referring to the direction of the net magnetisation vector when it is parallel to B_0, i.e. the situation prior to the first excitation pulse.

Angiogenesis

Phenomenon typical of tumours where new blood vessel growth is induced (mediated by angiogenic factors) to meet the increased oxygen demand required for rapid development. This is utilised in contrast enhanced scanning in cancer, where the preferential uptake of contrast agent by tumours improves its differentiation from normal tissue.

AngioMARK

Commercial name of a blood-pool agent undergoing clinical trials (Epix, Cambridge, MA). Also known as MS-325, it binds to albumin to extend its vascular half-life. The T_1 relaxivity is approximately ten times that of Gd-DTPA.

Anisotropy

Diffusion that is not the same in each direction, i.e. not isotropic. Usually implies some preferred diffusion direction and therefore can be used to elucidate structural information, e.g. white matter fibre tracts in the brain.

See also tensor, tractography and fractional anisotropy.

Anisotropic resolution describes spatial resolution that is not similar in each direction, e.g. in 2-D imaging where slice thickness is much greater than the in-plane resolution.

Anterior

Referring to the front side of the patient anatomy. It is at the top of an axial image and on the left of a sagittal image (see Figure 2).

See also posterior.

Apodisation

Essential part of processing MR spectroscopy data. It involves the multiplication of the free induction decay signal by an appropriate filter to improve signal-to-noise and reduce truncation artefacts in the final spectrum. Common filters include exponential, Lorentzian (a more rounded shape) and Gaussian (bell-shaped). Filters may typically have a linewidth of between 2 and 4 Hz.

Spatial apodisation reduces voxel–voxel contamination (voxel bleeding) in CSI.

Apparent diffusion coefficient

See ADC.

Array

A combination of RF surface coils to improve imaging coverage, taking advantage of the superior signal-to-noise of a single element without the compromise of poor sensitivity.

In a phased array design, consideration of the overlapping profiles has to be taken into account. Phased array coils, like surface coils, are typically used as receive-only coils (using the body coil to transmit). Coil arrays are now important in parallel imaging techniques.

Arrhythmia rejection window

The time interval in the cardiac cycle during which no imaging is acquired.

See also gating.

Artefact

Referring to any undesired signal contribution to the final image, which is not present in the real object/patient. Examples of common MR-related artefacts include ringing, phase wrap, susceptibility, chemical shift and ghosting. Artefacts may be distinguished by their appearance and the encoding direction in which they propagate.

Arterial input function

See also AIF.

Arterial spin labelling

Type of perfusion imaging that does not require a contrast agent. Works by acquiring a conventional image and a second image where the spins upstream are excited so that they do not contribute to the final signal. These images can then be subtracted to produce an image based on perfusion.

See also FAIR.

Artificial neural networks

Computational models that mimic aspects of brain function and are used to classify or solve problems. Typically, a data set is used to 'train' the model and then it is 'tested' on unseen data. They are designated as either supervised or unsupervised depending on the degree of user input at the training stage. Have been used in MRI for characterising tissues and tumour enhancement etc.

ASSET

Array sensitive encoding technique. The GE version of their parallel imaging method.

Asymmetric echo

See also partial echo.

Asymmetric sampling

Acquiring fewer data points on one side of the *k*-space origin as a method of speeding up imaging time.

See also partial *k*-space.

ATP

Adenosine triphosphate. Important compound observed in phosphorus spectroscopy relating to energy, and consisting of three spectral peaks referred to as α, β and γ with corresponding chemical shifts of -8 ppm, -15 ppm and -4 ppm, respectively.

See Figure 20.

Auto shim

Part of the scanner pre-scan routine. Currents in the shim coils are adjusted until the maximum homogeneity in the imaging volume is achieved. A figure for the linewidth of the water peak is usually provided as an indication of the shim. In imaging, auto shim is usually sufficient, whereas the stringent homogeneity requirement for MRS means that a manual shim is often necessary.

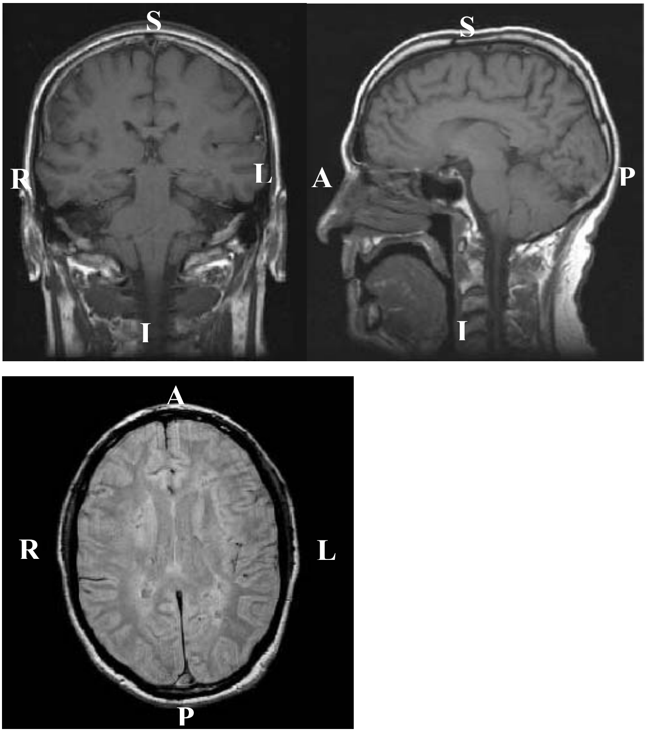


Figure 2. Images of the brain acquired in coronal, sagittal and axial (transverse) planes. Each image is labelled to indicate (R)ight, (L)eft, (A)nterior, (P)osterior, (S)uperior and (I)nferior directions.

Averaging

Improving the signal-to-noise ratio (SNR) by repeating the same part of a pulse sequence more than once. Works on the principle that signal is coherent whereas noise is random and its effect can be reduced by taking multiple measurements.

Increasing the number of signal averages extends acquisition time, with only a square root improvement in SNR.

See also NEX.

AX systems

Molecules which exhibit splitting of spectral peaks and where the chemical shift between the peaks is much greater than the coupling constant (J). An example is hexachloropropane. AX systems also demonstrate weak echo modulation.

See also J-coupling and AB systems.

Axial

2-D imaging plane taken in cross-section, dividing the subject into superior and inferior portions. Slice selection is (by convention) along the z-axis and the image is in the $x-y$ plane, i.e. perpendicular to B_0.

Sometimes referred to as transaxial or transverse.

See also coronal, sagittal and oblique.

MRI at high field

Signal-to-noise increases linearly with field strength, leading to images of improved quality. At 4.7 tesla, hair follicles are visible on images of the head. Improvements in signal can be traded off for faster or better resolution images. MRS also benefits from increases in chemical shift separation, separating previously unresolved spectral peaks, e.g. glutamate and glutamine in ^{1}H MRS. However, it's not all good news: susceptibility artefacts become worse and there are increased safety issues such as RF heating.

Bb

b-factor

Term relating to the degree of sensitivity of a diffusion-weighted sequence determined by the gradient characteristics. It is related to both the gradient amplitude and timing and for a typical Stejskal–Tanner bipolar sequence it is given by:

$$b = \gamma^2 G^2 \delta^2 (\Delta - \delta/3)$$

where G is the gradient amplitude, δ is the gradient duration, and Δ is the interval between the trailing-to-leading edge of the two gradient pulses. Typical values of δ and Δ are between 30 and 40 ms. The above equation may be modified to account for the rise time of the gradient plus contributions from normal imaging gradients.

Images at different b-values can be acquired to characterise the apparent diffusion coefficient (usually $0 < b < 1000\ \mathrm{s\ mm^{-2}}$).

See also diffusion time.

B_0

Conventional notation referring to the main static magnetic field produced by the scanner (the main field). The direction of the main field is usually assigned the z-direction. Typical clinical scanners operate at 1.5 tesla. Theoretically, the signal-to-noise ratio (SNR) increases as $B_0^{3/2}$, but due to changes in relaxation times, principally T_1, the actual dependence is more linear.

See also T_1.

B_0 correction

Use of the water resonance peak as a chemical shift reference for the assignment of other metabolites, whose frequencies may alter across a CSI dataset due to B_0 inhomogeneity.

B_0 inhomogeneity

Changes in the main magnetic field due to either inherent manufacturing limitations or the introduction of some material into the scanner.

See also homogeneity.

B_1

Notation for the time-varying magnetic field produced by the radio-frequency (RF) coil, and applied to excite and refocus spins, etc. Its direction must be perpendicular to B_0 and applied at the Larmor frequency. By convention the orientation of this field is in the $x-y$ plane (see x-direction). Typical values are of the order of 0.01 mT.

See also RF power and flip angle.

B_1 inhomogeneity

Changes in the RF field leading to artificial signal variation in the final image. The main contribution is from the B_1 profile of the receiver coil and the effect is prominent with surface coils.

See also homogeneity and SCIC.

B_1 doming

Inhomogeneity observed in images at high field (3.0 tesla and above) due to the increased dielectric effect, which produces a standing wave artefact. Results in a bright signal at the centre of the image. The effect can be problematic in phantom images and limits the maximum diameter of the test object. B_1 doming is accentuated by poor RF penetration leading to lower signal at the periphery.

B_1 profile

The sensitivity of a RF coil to magnetic field (in the case of a receiver) or the magnetic field strength produced as a function of distance from that coil (for a transmitter). Surface coils have characteristically poor reception profiles.

See also parallel imaging and coil uniformity correction.

Balanced echo

See *b*FFE

Bandwidth

The frequency range of the receiver. Can be related to the frequency used to encode each pixel and therefore determine the extent of the chemical-shift artefact. For example, for a 256 frequency matrix and bandwidth of 32 kHz, there are 125 Hz per pixel so the fat–water shift is approximately 2 pixels. Typical bandwidths vary from 6.5 kHz to 1 MHz.

See also variable BW.

Bandwidth per pixel

Sequence setting for adjusting the receiver bandwidth on Siemens scanners. It is equal to the receiver bandwidth divided by the imaging matrix in the frequency encoding direction.

See also chemical shift artefact.

Baseline

Referring to signal intensity or an image acquired at some reference condition, e.g. a pre-contrast image prior to contrast enhancement or a resting state in some fMRI experiment.

In MRS it refers to the background noise in the spectrum.

Baseline correction

Method of processing MR spectra to remove the effect of broad spectral humps from immobile macromolecules with short T_2^* values, which produce an elevation of the spectral baseline.

bFFE

Abbreviation for balanced fast field echo. A Siemens/Philips sequence, which may be described as a 'true' FISP sequence, i.e. it uses balanced re-winding gradients in all three directions to reset the phase at the end of each TR.

See also FISP.

Bind (image)

Process by which images from two separate series are appended to produce a new image series. Also called concatenation.

Binomial pulse

Type of composite RF pulse with flip angles that are applied in a binomial series. (e.g. 1:−1, or 1:−2:1). Rely on the dephasing of water and fat to suppress the fat signal.

Bio-effects

Referring to any biological effects on the human body caused by interaction with the MR scanner. These effects can be catagorised into (i) static field (B_0) effects, (ii) time-varying field effects (gradients) and (ii) radio-frequency (B_1) effects. There are no known long-term or irreversible effects from exposure to fields below 10 tesla. Some studies have shown short-term 'mating-avoidance' in small mammals at 3.5 tesla. Rapidly varying magnetic fields produced by the imaging gradients may cause peripheral nerve stimulation. Excessive radio-frequency interaction in patients will lead to tissue heating (see SAR).

See also static field limits.

Reference F. G. Shellock (2001). *Magnetic Resonance Procedures: Health Effects and Safety*. Florida: CRC Press.

Birdcage

A very efficient RF coil design utilising many regularly spaced conductors giving its characteristic appearance and name (Figure 24). Also referred to as a distributed capacitance coil. Most head coils are of this design, typically used as a transceiver. Produces very homogeneous imaging profiles, particularly in the axial plane.

See also saddle coil, solenoid and surface coil.

Reference C. E. Hayes, W. A. Edelstein, J. F. Schenck, O. M. Mueller &M.Eash(1985).Anefficient,highlyhomogeneousradiofrequency coil for whole-body NMR imaging at 1.5 T. *J. Magn. Res.*, **63**, 622–8.

Bit

Smallest digital data unit (1 or 0). Eight bits make up one byte; 1024 bits equal 1 kB. Image data (i.e. pixel intensity values) are typically stored as unsigned integers in 16 bits, although this varies. See byte for description of data types.

Black blood

MR Angiography technique in which blood (flowing spins) appears dark compared to stationary tissue.

See also high velocity signal loss and white blood.

Blipped EPI

EPI sequence in which the phase encoding step is incremented by the same amount while the frequency gradient is switched to sample *k*-space in a regular trajectory.

Other methods include spiral and constant EPI.

Bloch equations

Equations first used by Felix Bloch to described NMR. They were later modified to incorporate the effects of relaxation. (See Appendix III.)

Bloembergen, Purcell and Pound equation

The equation that relates tissue relaxation times to molecular tumbling rates and field strength. The motion of the molecules can be represented by the correlation time or the time interval between collisions (of the order of 10^{-12} s). This will be influenced by structure and temperature, and in turn effect relaxation times. For effective T_1 relaxation the tumbling rate must be close to the Larmor frequency. In the case of either free water (e.g. cerebrospinal fluid, CSF) or bound water, there are relatively few molecules at this rate and T_1 relaxation is long. In terms of T_2, slow-moving molecules such as bound protons (e.g. proteins) experience net changes in local field variations and have short values, but as tumbling rates increase these effects average out and longer T_2 values persist. Generally, tissue relaxation times will be a weighted average of free and bound components. The equations are detailed below:

$$\frac{1}{T_1} = C\left[\frac{\tau_c}{1+\omega_0^2\tau_c^2} + \frac{4\tau_c}{1+4\omega_0^2\tau_c^2}\right]$$

$$\frac{1}{T_2} = \frac{C}{2}\left[3\tau_c + \frac{5\tau_c}{1+\omega_0^2\tau_c^2} + \frac{2\tau_c}{1+4\omega_0^2\tau_c^2}\right]$$

where τ_c is rotational correlation time, C is a constant dependent on the dipole–dipole interaction and ω_0 is the resonant frequency.

The T_2 equation contains a zero-frequency component, which demonstrates the weak field strength dependence of T_2. In contrast, T_1 values become longer as field strength increases, as the proportion of spins tumbling at the resonant frequency is reduced.

See also T_1 and T_2.

Blood pool agent

Type of experimental contrast agent with a long vascular half-life remaining in the blood much longer than conventional contrast agents, which enter extravascular space because of their small molecular size. This has advantages for contrast-enhanced MRA. Many of the agents, e.g. angioMARK, bind reversibly to albumin.

Reference M. Saeed, M. F. Wendland & C. B. Higgins (2000). Blood pool agents for cardiovascular imaging. *J. Magn. Reson. Imag.*, **12**, 890–898.

Blood-suppressed preparation

Preparatory pulse sequence which nulls blood thereby creating a black-blood image. Works by using a double inversion pulse, first non-selective, the second re-inverting the slice thereby leaving it unchanged. The sequence is then timed so that blood flowing into the slice has reached the null point at the time of signal detection.

Blooming ball artefact

Large circular signal voids or enhancements due to susceptibility artefacts especially seen at the end of biopsy needles when the needle trajectory is along the direction of B_0.

See also MR compatible.

Reference J. S. Lewin, J. L. Duerk, V. R. Jain, C. A. Petersilge, C. P. Chao & J. R. Haaga (1996). Needle localisation in MR-guided biopsy and aspiration: effects of field strength, sequence design and magnetic field orientation. *Am. J. Radiol.*, **166**, 9.

Blurring

The effect of reduced spatial resolution when using long echo trains in FSE type sequences. It is caused by increased differences between the signal echoes used and the overall effective TE.

Body coil

The RF coil usually integrated into the bore of the scanner for imaging with a large field of view (typically 40 cm). See Figure 25. It is normally operated as a transceiver, and often a birdcage design.

Boil-off

Relating to the rate at which the cryogens need replenishing to maintain the critical temperature of the superconducting magnet. Typical values are around $0.03\ \mathrm{l\ h^{-1}}$.

BOLD

Blood oxygen level dependent contrast. Type of functional MR technique that indirectly monitors the haemodynamic response to brain activation. Increased oxygen fraction in the blood caused by local neuronal activation reduces the paramagnetic effect of deoxyhaemoglobin causing a signal increase on T_2- or T_2^*-weighted images.

The response lags the neuronal firing, by several seconds. Often the signal is characterised by an initial dip as the increased demand for oxygen uses up the local supply before being replenished. There is also typically a characteristic overshoot in the initial 'on' condition and sometimes an accompanying 'undershoot' at the end of the stimulus. This is thought to be mediated by a slow-reacting change in blood volume.

Reference S. Ogawa, T. M. Lee, A. S. Nayak & P. Glynn (1990). Oxygen-sensitive contrast in magnetic resonance imaging of rodent brain at high fields. *Magn. Reson. Med.*, **14**, 68–78.

Boltzmann distribution

The population distribution of spins between the spin up and spin down state. At room temperature and at clinical field strengths, the tiny majority in the ground state (spin up) is only 10^{-6}.

The ratio of the spins in the two states is given by:

$$n_\beta / n_\alpha = \exp(-\Delta E/\kappa T)$$

and the difference in populations can be approximated to:

$$n_\beta - n_\alpha \cong n\gamma\hbar B_0/2\kappa T$$

where n_α and n_β are the number of spins in the spin-down and spin-up state, respectively, and ΔE is the energy difference between these states.

Bolus

Referring to the delivery of contrast agent (usually intravenously). It may be performed by hand or preferentially by an automatic injector, triggered from the control room, to deliver a tight reproducible dose.

See also AIF and transit time.

Bolus timing

The synchronisation between the arrival of the contrast agent (given by the mean transit time) and the acquisition of the imaging sequence.

Bolus tracking

MRA technique that monitors the passage of contrast agent using rapid 2-D imaging in order to initiate the accurate timing of a subsequent sequence. The initiation may be automatic or more often manually performed. Called BolusTrak on Philips systems. Historically referred to as 'MR fluoroscopy'.

Bonferroni correction

Statistical adjustment of some probability statement to account for multiple comparisons of data. For example, if 20 tests are carried out with P-value $= 0.05$ significance level, then on average one test will demonstrate an erroneous significance by chance (see statistical errors). The correction accounts for this by dividing the single test p-value by the number of tests. In fMRI this is equivalent to dividing the p-value by the number of pixels.

Reference B. S. Everitt (2003). *Medical Statistics from A to Z,* Cambridge: Cambridge University Press.

Bore

The diameter of the MR scanner. More specifically referred to as the patient bore, indicating the actual width of the final system rather than the diameter of the main windings. Modern scanners have a patient bore of around 50 cm, whereas the diameter of the main coil windings may be 1 m. See Figure 25.

Bore liner

Use of a plastic insert between patient and scanner bore to reduce acoustic noise. Accounts for a noise reduction of between 10 and 15 dB.

Bounce point artefact

The phenomenon observed in inversion recovery where two tissues with different T_1 values recover to the same magnitude either side of the null point ($M_z = 0$) so that they appear isointense in the final image. They can only be distinguished at a common boundary, due to the signal void caused by cancellation of equally negative and positive signal.

Bound protons

The opposite to mobile or free protons (e.g. water, CSF). Large macromolecules such as proteins form a hydration layer of tightly bound water molecules. This reduces molecular tumbling rates and increases correlation times. T_1 values are long but corresponding T_2 values are extremely short so that they are 'invisible' on MR images. These molecules may be investigated using magnetisation transfer imaging.

Box car

A type of fMRI paradigm involving regular on and off stimulus periods, typically lasting 20–30 s each. More sophisticated studies use event-related schemes.

BPH

Benign prostatic hyperplasia. Common benign disease found in the prostate. Characterised by mixed signal changes on T_2-weighted images. May cause either an increase or decrease in the levels of citrate on MRS depending on type.

BPP equation

See Bloembergen, Purcell and Pound equation.

Breath hold

Utilising very short scan times so that it is possible for the patient to hold their breath. The patients are asked to breathe normally and then hold on exhalation, reducing motion artefacts caused by respiration.

Bright blood

See white blood.

Bright fat

The characteristic high signal appearance of fat on T_2-weighted FSE images due to breakdown of *J*-coupling effects in the lipid molecule caused by the rapid RF train.

See also DIET.

Brodmann areas

Designation of specific parts of the brain based on their function, although in his work (1909) Brodmann distinguished each part by the visual appearance through a microscope. Often used in reporting fMRI activation.

See also Talairach space.

Bruker

Commercial company that deals specifically with high field magnets offering small bore designs for animal studies (4.7 to 11.7 tesla) but also whole-body systems up to 9.4 tesla (head only).

Byte

Binary representation of data. One byte is equal to 8 *bits* numbered 1,2,4, . . . , 128 with a range of 0 to 255. Four bytes are usually referred to as a word. Commonly image data is stored as a 16-bit short integer representation (2 bytes), giving a range from 0 to 65 535. On PC and Unix workstations the magnitude of the left or right byte is different. This is referred to as either little- or big-endian.

Common data types you may come across are integers and floats. Integers (whole numbers) are typically stored in two or four bytes (the former classified as a short). These can be unsigned (as in image data) or signed, in which case the last bit is reserved for the sign so that a 2-byte number is restricted to a range of −32 768 to +32 768. Decimal numbers are called floats and represent the number and its exponent in 4 bytes. Double precision types are allocated 8 bytes (2 words).

Cc

Cable loss

Correction factor used in the RF coil configuration file of the scanner. It takes into account any signal losses that result from an impedance mismatch between the coil and the connecting cable.

Carbogen

A mixture of air composed of 95% O_2 and 5% CO_2. It is used to study perfusion via BOLD effects and also in ventilation imaging.

Carbon

^{13}C is the MR visible isotope of carbon (as opposed to ^{12}C, which is naturally abundant but not MR visible). It has a chemical shift range of 200 ppm and a resonant frequency at 1.5 tesla of 16.1 MHz.

Cardiac MR

The increased use of MRI to provide both anatomical and functional images of the heart. Traditionally, this has been done with nuclear medicine and PET. Modern MR scanners (faster gradients, improved gating techniques, etc.) have meant that more cardiac MR is now performed. Stress-perfusion tests compare normal images with those acquired after administration of a suitable stress-perfusion agent. This induces stress on the heart and permits the examination of infarcts more readily.

See also cardiac gating and spin tagging.

Cardiac gating

See ECG gating.

Carr–Purcell

or CP sequence, basic multiple spin-echo sequence for measuring T_2. Later modified to produce the CPMG sequence.

CD

Compact disc. Data archiving medium that is PC compatible. Typically holds 650 MB of image or screen-shot data. Modern scanners have on-board CD writing capabilities.

See also DAT.

Central *k*-space

The inner portion of *k*-space data corresponding to the bulk of image signal. Also referred to as low order phase.

Central point artefact

Image artefact resulting in a bright spot at the centre of an image. It is caused by a DC offset in the receiver. Occasionally, very stable RF interference may appear as a spot on the image rather than the more usual line.

Centre frequency

The frequency to which the RF coils are tuned during the pre-scan routine. The coils are tuned each time to adjust the frequency to which (usually) water is assigned. From this, other frequencies and bandwidths can be properly assigned, for example the fat peak in CHESS.

Centric *k*-space filling

Conventionally, *k*-space is filled in a sequential or linear fashion (i.e. highest negative gradient steps to highest positive steps). In centric filling, the outer edges of *k*-space, corresponding to the high positive and negative phase steps, are filled first. As a consequence, the bulk MR signal is acquired at the end of the sequence. Alternatively, reverse or concentric filling acquires the centre of *k*-space first. The filling order becomes important in certain situations, for example in gating or contrast-enhanced MRA.

See also *k*-space ordering and trajectory. See Figure 15.

Cerebral blood flow (volume)

Perfusion parameters specifically related to imaging in the brain. Cerebral blood flow (CBF) is the perfusion rate per unit of tissue mass. It is related to the peak signal loss in a dynamic susceptibility contrast (perfusion-weighted) scan. Cerebral blood volume (CBV) is the total blood volume in the region of interest and is estimated by the area under the curve (or negative enhancement integral). CBV is affected by many pathological conditions.

CBV is related to CBF by:

$$CBV = CBF \times MTT$$

where MTT is the mean transit time.

To gain an accurate measure of CBF the arterial input function (AIF) needs to be deconvolved from the tissue signal.

See also perfusion imaging.

Reference F. Calamante, D. L. Thomas, G. S. Pell *et al.* (1999). Measuring cerebral blood flow using magnetic resonance imaging techniques. *J. Cereb. Blood Flow Metab.*, **19**, 701–735.

Cerebrospinal fluid

Fluid that circulates around the spinal cord and brain and acts as protection and nourishment. Has long T_2 and T_1 relaxation times that give it a characteristic appearance on MRI (see Figure 30).

Chemical shift

The local change in resonant frequency due to different chemical environments. Forms the basis of MRS, i.e. the identification of molecules depending on their chemical shift. Specifically, a molecular electron cloud shields the proton from the full extent of B_o reducing the field as:

$$B' = B_0(1 - \sigma)$$

where σ is the shielding constant. First observed in metals by Knight (formerly known as Knight shift). See ppm.

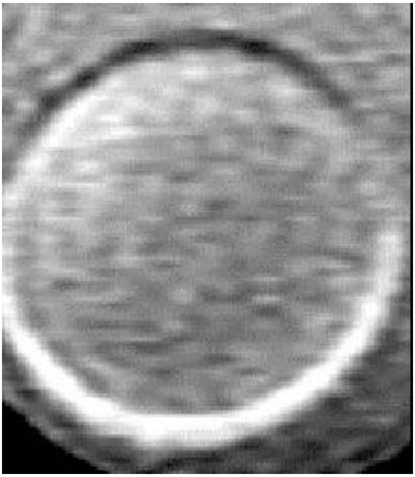


Figure 3. An egg gives a clear demonstration of the chemical shift artefact: a dark band (signal void) at the top and bright band (overlap) at the bottom.

Chemical shift artefact

Characteristic appearance of bright and dark bands due to the mismapping of fat and water, which coexist in the object but become spatially distinct in the image. Sometimes referred to as relief artefact due to its appearance. It is due to the finite frequency range assigned to each pixel and is therefore only evident in the frequency encoding direction. The artefact may be reduced by increasing the receiver bandwidth, to allow for the frequency difference between water and fat, which is 220 Hz at 1.5 tesla. The artefact is worse at high field.

The chemical shift is so large in EPI that fat suppression or water-only selective RF pulses must be employed. In EPI, the artefact is present in the phase-encoding direction.

Chemical shift imaging

or CSI. 2-D or 3-D MRS technique in which a volume is localised and this is subdivided into smaller contiguous voxels using phase encoding. The spatial resolution of each voxel is limited to typically 1 cm^3 but this may be reduced to 0.2 cm^3 if a surface coil is used. In true CSI a metabolite map is produced.

See also MRS, multiple voxel, PROSE, PRESS and STEAM.

Chemical shift ('of the second kind')

Signal voids observed in gradient echo imaging due to phase differences between fat and water. It can be eliminated by acquiring the image at specific echo times so that the fat and water are in phase (4.2 ms at 1.5 tesla). Some scanners permit the user to select the echo time to be 'in-phase' or 'out-of-phase'.

CHESS

Chemical shift saturation. A method of fat suppression where a narrow bandwidth RF pulse (typically 50 Hz) is centred on the fat resonance and is used to excite the fat signal only. This is then dephased by gradients prior to the acquisition of the main imaging sequence. See Figure 32.

Choline

Metabolite peak observed in proton spectroscopy (also seen in Phosphorus MRS as phosphocholine). It is indicative of cell turnover, and its elevation is thought to be a marker of cancer. Observed at 3.22 ppm. See Figure 27 and Appendix VI.

Chunk

See slab.

Cine

Viewing sequential images in a movie loop. Useful for detecting contrast changes or studying physiological motion, e.g. cardiac MRI. Images may be viewed in temporal or spatial order and can be played back in a loop or yo–yo back and forth.

Circularly polarised

Another term for quadrature detection/transmission RF coils.

CISS

Constructive interference steady state. Siemens sequence that produces strongly T_2-weighted images by combining two FISP echoes. Largely redundant since the introduction of 3-D FSE sequences.

See steady state.

Citrate

Important ^{1}H MRS peak observed uniquely in high concentrations in the prostate gland. Thought to be an important marker of prostate cancer, with levels being reduced in malignant disease. Observed at 2.6 ppm, it is designated an AB system, with a chemical shift separation of 15.4 Hz and a coupling constant of 7.8 Hz.

See Appendix VI for the chemical structure.

Reference F. Schick, H. Bongers, S. Kurz, W. I. Jung, M. Pfeffer & O. Lutz (1993). Localised proton MR spectroscopy of citrate in vitro and of the human prostate in vivo at 1.5 T. *Magn. Reson. Med.*, **29**, 38–43.

Claustrophobia

The fear of enclosed spaces sometimes encountered by patients having an MR scan. Figures vary depending on scanner type and method of entry (supine, prone) but may be between 2 and 10%. In severe cases it may cause the examination to be aborted. Methods of reducing this include bore lighting, music and ventilation.

CNR

See contrast-to-noise ratio.

Coil uniformity correction

Method of improving image uniformity by correcting for the inhomogeneous reception profile of RF coils. Usually involves weighting the image by an appropriate sensitivity function (determined in a proton density image, for example). The GE method is known as SCIC. On Philips systems there are three levels of correction: strong, weak and CLEAR (constant level appearance).

See also B_1 inhomogeneity.

Composite pulses

See binomial pulse.

Conjugate symmetry

Property of *k*-space by which the data values on one side of *k*-space are identical to the values at the mirror location through the origin:

$$S(k_{PE}, k_{FE}) = S^*(-k_{PE}, -k_{FE})$$

Permits the interpolation of missing data when only half of *k*-space has been acquired (see partial fourier, partial echo). Also referred to as Hermitian symmetry. In practice, slightly more than 50% of *k*-space is acquired and the extra data can be used to correct for any phase errors.

Constant EPI

EPI method where the phase-encoding gradient is continually applied producing a zig–zag *k*-space trajectory.

See also spiral and blipped EPI.

Contiguous

Referring to adjacent slices with zero gaps. Leads to cross-excitation due to overlapping slice profiles.

Also see intervleaved.

Continuous wave NMR

Technique whereby resonance is detected from applying a continuous sweep of radiofrequency.

See also adiabatic pulse.

Contraindications

Presentation of a patient in such a way as to prevent the acquisition of the MR scan. For example, patients with certain implants, devices, etc.

See projectile, pregnancy and pacemaker.

Contrast

The visual difference in signal intensities between adjacent structures on an image. It may be quantified by expressing the difference in signal between two structures divided by the summation or by measuring contrast-to-noise.

Contrast agents

A substance (usually an exogenous chemical agent) that is used to alter the signal contrast within the image. The majority of contrast agents usually shorten relaxation times, but spin-density agents also exists (e.g. glucose, deuterium oxide). Agents of the former type can be subdivided into paramagnetic and superparamagnetic iron oxide (SPIO). Of the paramagnetic types, the most common are the extracellular gadolinium-based agents. There are also albumin-binding blood pool agents and non-gadolinium agents, e.g. manganese.

Agents are typically administered intravenously followed by a saline flush.

See also USPIO, endogenous, Gd-DTPA, Gd-DOTA.

Contrast enhanced

MR images, acquired following the administration of paramagnetic contrast agents to improve signal differences in

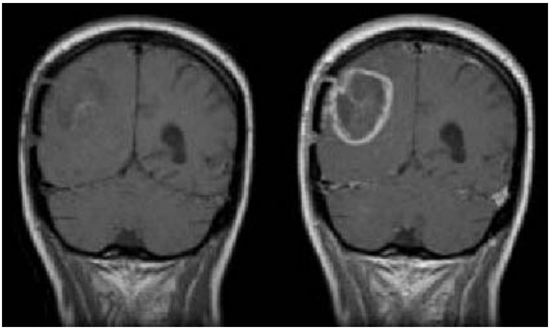


Figure 4. Example of **contrast enhancement**. (*left*) A pre-contrast coronal brain image. (*right*) Following administration of **Gd-DTPA**. The T_1-weighting of these images highlights the disruption to the blood–brain barrier.

tissues. The majority of studies utilise T_1-weighted images that demonstrate increased signal in the presence of the agent. Useful in the study of tumours that demonstrate a preferential uptake of these agents due to angiogenesis.

Contrast enhanced MRA

The use of MR contrast agents to image the vascular tree directly. The main advantage over TOF techniques is that there is no reliance on saturation effects, so that slice thickness and flow orientation is not a limiting factor. The technique is limited at the moment due to the extracellular nature of current contrast agents, which cause an unwanted background enhancement and necessitate accurate bolus timing.

Reference M. R. Prince, E. K. Yucel, J. A. Kaufman *et al.* (1993). Dynamic gadolinium-enhanced three-dimensional abdominal MR angiography. *J. Magn. Reson. Imag.*, **3**, 877–881.

Contrast phantom

Specifically designed test object for examining contrast properties in different image sequences.

See gel phantoms and quality assurance.

Contrast-to-noise

A quantitative measure of relative signal differences. Also referred to as CNR (or sometimes C/N), and defined as:

$$\mathrm{CNR} = (S_1 - S_2)/\left(\sigma_1^2 + \sigma_2^2\right)^{1/2}$$

where S and σ are the mean and standard deviation of measured signal (1) and noise (or some other signal, 2), respectively.

See also SNR.

Control room

Secure area from where the scanner is operated by radiographic staff and where some minimal image processing takes place.

See also scan room.

Copper

Material used in the RF screening of the scan room. Copper is also used (in compounds such as copper sulphate) to dope water in phantoms. The T_1 and T_2 relaxivity values for copper are similar (for Cu^{2+} ion this is approximately $0.7\ mM^{-1}\ s^{-1}$).

Coronal

Image plane acquisition that divides the subject into anterior and posterior, i.e. the slice selection is in the y-direction and the in-plane directions run right-to-left and head-to-foot. May also be called frontal plane.

See also sagittal, axial and oblique. See Figure 2.

Correlation coefficient

Statistical parameter indicating how closely matched two sets of data are. Particularly useful in fMRI analysis to correlate pixel intensity changes with the stimulus reference pattern. Values range from -1 to 1, with the extreme values indicating a perfect correlation (the sign indicating the direction of the relationship) and zero indicates no correlation. Pixels with high positive values may be identified in colour and overlaid onto standard anatomical images to produce maps of brain activation. See Figure 7.

Correlation time

The average time interval before a molecule collides (τ_c). Solids have long correlation times whereas values in liquids and gases are shorter. Higher temperatures also reduce this value. Related to molecular tumbling rate.

See also Bloembergen, Pound and Purcell equation.

COSY

Correlated spectroscopy. Method for representing peak resonances on two-dimensional axes to demonstrate J coupling.

Cortical flattening

fMRI post-processing method, which removes the undulations of the cerebral cortex to localise the region of activation accurately.

Cortical inflation

fMRI post-processing method, which involves transposing image data into a standardardised brain volume for cross-study comparisons.

CPMG

The Carr–Purcell–Meiboom–Gill sequence used to measure T_2. The basic unit (Carr–Purcell) is a multiple spin-echo sequence with signal decay measured at different echo times. In the modified sequence (CPMG), the phase (direction) of the 180° refocusing pulse is alternated to prevent compounding errors in pulse angles and therefore produce a more accurate T_2 value.

Reference A. A. Maudsley (1986). Modified Carr–Purcell–Meiboom–Gill sequence for NMR fourier imaging applications. *J. Magn. Reson.*, **69**, 488–491.

Creatine

Proton metabolite observed at 3.02 and 3.94 ppm. Reduced in tumours. See Figure 27 and Appendix VI.

Cross-excitation

Refers to the erroneous excitation of an adjacent slice due to imperfect slice profiles. Can be reduced by interleaving the slice selection or by including slice gaps in-between slices (usually 10% of the nominal slice thickness). Not to be confused with cross-talk.

Cross-talk

The exchange of energy between spins in adjacent slices due to T_1 relaxation.

Crusher gradients

Application of gradients to eliminate (by dephasing) unwanted signal.

See also spoiling.

Cryogens

The liquids (usually helium) used within the scanner cryostat (see Figure 25) that maintain the critical temperature of the superconducting magnet. Need to be replenished on a monthly basis due to boil-off. Earlier scanners also used liquid nitrogen. The cryostat is vented at the top of the scanner to ensure the safe removal of the cryogens in the advent of a quench.

Cryoshielding

Reducing the boil-off rate of the cryogens by externally cooling the cryostat.

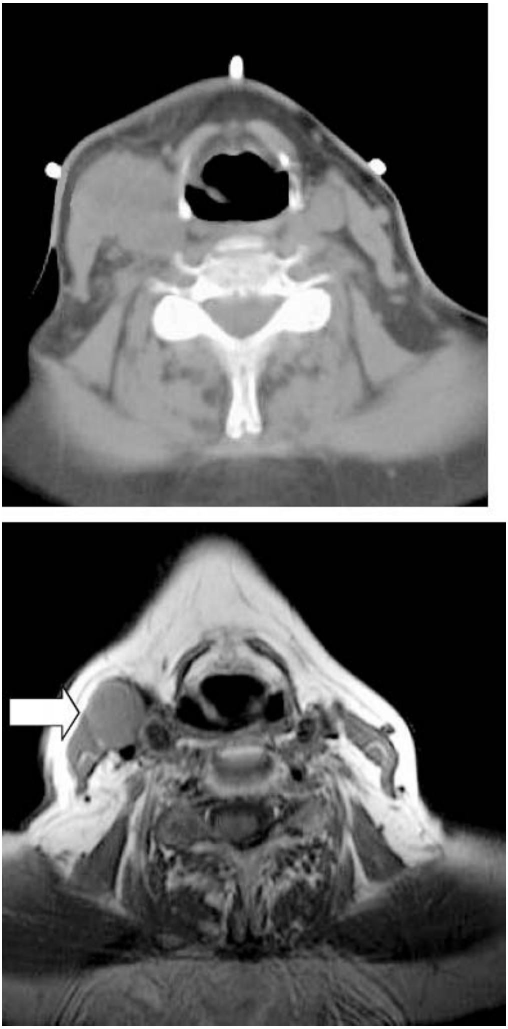


Figure 5. Here a **CT** image on the top is compared to MRI on the bottom. The latter may be used in radiotherapy planning to provide extra tumour detail (arrow). (Courtesy of A. W. Beavis, Princess Royal Hospital, Hull).

CSF

Cerebrospinal fluid.

CSI

Chemical shift imaging.

CT

Computer tomography (also formally known as CAT or computer assisted tomography). Medical imaging method utilising X-rays to obtain multi-planar images, first used in 1973. Unlike MRI, it has little soft-tissue contrast. It is still the modality of choice in certain areas, for example in radiotherapy planning, where the signal attenuation is used to estimate electron density, or in trauma or in spinal injuries where analysis of bone is crucial.

CTL coil

RF receive-only surface coil array with selectable elements for imaging either the cervical, thoracic or lumbar spine.

FMRI and BOLD

Typically, the signal change associated with BOLD activation is only a few per cent at 1.5 tesla. Owing to the doubling of signal and increased susceptibility effects, the effect may increase by a factor of 4 at 3.0 tesla. This may lead to the investigation of brain functions previously unseen at 1.5 tesla. BOLD changes are an indirect haemodynamic response to neuronal activation and lag behind by a few seconds.

Dd

DAC

A digital-to-analogue converter. This is hardware, which turns the digital signal generated by the double balanced mixer into an analogue signal for transmission.

See also ADC.

DAT

Digital tape archiving medium holding approximately 1.3 GB of images. Being phased out in favour of optical discs (OD).

Daum needles

Specially coated MR compatible biopsy needles to reduce susceptibility artefacts.

d*b*/d*t*

Pronounced 'd*b* by d*t*'. This refers to the rate of change of magnetic field within the gradients. A high value of this improves imaging speed but can lead to peripheral nerve stimulation.

DCIS

Ductal carcinoma in situ. Type of breast cancer that is difficult to detect and is being increasingly examined with MRI.

Dead time

The period following the echo time (TE) and prior to the application of the next 90° RF pulse. During this time other adjacent slices are excited thereby improving the efficiency of 2-D imaging. For example, in a spin-echo sequence with TE/TR = 200 ms/1 s, five slices can be acquired theoretically per TR.

Decay

Describing any loss of MR signal, usually due to dephasing effects.

Decimation

The opposite of interpolation.

DEFT

Abbreviation for the driven equilibrium fourier transformation sequence.

See driven equilibrium.

Demodulation

The removal of the RF component of the measured MR signal to leave an audiofrequency (AF) signal. It corresponds to multiplication of the signal by a sinusoid at the resonant frequency. This is then passed onto the analogue-to-digital converter for processing.

Dephasing

Loss of phase coherence of spins due to interaction with neighbouring spins (T_2) and inhomogeneities in the magnetic field (combined effect described by T_2^*).

Dephasing lobe

Part of the slice selection and frequency encoding gradient that is applied in the opposite sense to ensure that there is no net phase change when the gradient is applied. The amplitude (area on a pulse sequence diagram) of the lobe is half that of the main gradient. See Figure 21.

DESS

The double echo steady state sequence. This combines a FISP echo and a subsequent PSIF echo to produce high resolution images with strong fluid signal (large T_2-weighting). Used mainly in orthopaedic imaging.

Deuterium

Isotope of hydrogen with a mass number of 2 (proton and neutron). It has a spin quantum number equal to 1.

Dewer

MR-compatible container taken into the scan room; used to transport/re-fill cryogens.

DEXA

Dual energy X-ray absorptiometry. A method for assessing bone mineral density in the examination of osteoporosis.

Modern high-resolution MRI is being used increasingly in bone imaging, with spatial resolution of between 50 and 200 μm.

Diamagnetic

Defined as negative susceptibility: the field induced within the material when placed in an external magnetic field acts in the opposite direction. Examples include water.

DICOM

Digitial imaging and communications in medicine. Industry standard of medical image type permitting ease of data transfer between different proprietary devices. The DICOM standard is an enhancement of previous ACR–NEMA standards (American College of Radiology and National Electrical Manufacturers Association). A DICOM image will consist of an image header containing tags or entries of information that may be interpreted in a known fashion.

See http://medical.nema.org

Dielectric effect

Resonance effect especially seen at high field in materials with a high dielectric constant, ε (e.g. water with $\varepsilon = 80$) producing a standing wave artefact. Can be reduced in phantoms by using smaller diameter objects or materials with lower constants (e.g. oil, $\varepsilon = 3$).

See also B_1 doming.

Reference P. S. Tofts, G. J. Barker, T. L. Dean, H. Gallagher, A. P. Gregory & R. N. Clarke (1997). A low dielectric constant customised

phantom design to measure RF coil non-uniformity. *Magn. Reson. Imag.*, **15**, 69–75.

DIET

The delayed interval echo train sequence. The use of an increased echo spacing between the first pair of RF pulses in a FSE sequence in order to conserve the *J*-coupling effects in fat and therefore create a more typical spin-echo contrast.

See also bright fat.

Diffusion

See DWI.

Diffusion ellipsoid

Three-dimensional representation of the diffusion tensor using an ellipsoid. The shape indicates the degree of anisotropy, the size gives the magnitude of diffusion and the orientation demonstrates the preferred diffusion direction. Typically, shapes may be spherical (isotropic in x,y,z), disc-shaped (isotropic in two planes) or cigar-shaped (preferred diffusion in one direction).

Diffusion tensor

See DTI.

Diffusion time

Related to the time between the bipolar gradient pulses used in a typical DWI sequence. Increasing this time makes it possible to examine restricted diffusion. It is equal to the term $\Delta - \delta/3$ in the *b*-factor equation.

Dimeglumine gadopentatate

Chemical name for Gd- DTPA. Marketed by Schering as Magnevist.

Dipole

The concept of a north–south magnetic field or moment produced by a spinning nucleus.

Dipole–dipole interactions

The interaction between two nuclear spins. The directional nature of a dipole means that, depending on the position of one dipole with respect to another, the magnetic field is either augmented or reduced. In a moving water molecule this can be as much as ±7 G. These interactions are the most dominant in causing T_1 and T_2 relaxation. The magnitude of the interactions is given by:

$$3\cos^2\theta - 1$$

Where θ is the angle between each dipole. This leads to the so-called magic-angle effect at $\theta = 54.7^\circ$ (zero interaction).

In contrast, *J*-coupling refers to interactions between spins of the same molecule via electron cloud distortions.

Dispersion

The separation of adjacent MR spectroscopy peaks. It increases linearly with field strength, enabling closely spaced peaks such as glutamate and glutamine to become resolved at fields of 3.0 tesla and above.

See also chemical shift.

Distance factor

Alternative name given for slice gap on Siemens scanners where the separation between slices is determined as a percentage of the slice thickness used.

Distortion

Referring to any differences between the final image and the actual object shape. Principally caused by inhomogeneity in B_0 and also non-linearity of the gradients. The latter can be reduced by using a high bandwidth (>32 kHz). Can be further classified into geometric distortion and linearity.

Reference C. S. Moore, G. P. Liney & A. W. Beavis (2003). Quality assurance of CT and MR registration for radiotherapy planning of head and neck cancers, *Clin. Oncol.*, **15**(2), S8.

Dixon

Method of fat suppression making use of the phase differences between fat and water. Two images are acquired: one with a suitable echo-time so that fat and water are in phase, the second with fat–water out of phase, and a subtraction is subsequently taken. In the three-point Dixon method, a third image with the same in-phase echo time is acquired to correct for B_0 inhomogeneities.

See also OOPS.

Doping

The use of a chemical agent to enhance the relaxation rate of water and therefore mimic in vivo signal characteristics in test objects or phantoms. Common agents include gadolinium, copper, nickel, manganese compounds and agarose gel.

See also relaxivity.

Dotarem

A less commonly used gadolinium-based contrast agent.

See Gd-DOTA.

Double balanced mixer

Produces an amplitude modified RF waveform suitable for slice selection by combining the RF signal with an audio-frequency (AF) waveform.

See also ADC and DAC.

Double donut

Specific design of an open magnet with a vertical rather than a horizontal opening.

Double oblique

Images that are acquired in a non-orthogonal or oblique plane and also rotated in one additional axis.

Doublet

MRS spectral peak that appears as two closely spaced lines due to *J*-coupling.

Draining vein

Problem related to the BOLD effect, that activation is inferred from the blood response and may be reflecting changes in veins. This results in a spatial shift by a few mm relative to the true neuronal activation.

See fMRI.

Reference R. Turner (2002). How much cortex can a vein drain? Downstream dilution of activation-related cerebral blood oxygenation changes. *Neuroimage*, **16**, 1062–1067.

DRESS

Depth resolved surface coil spectroscopy. The simplest MRS technique involving a 90° excitation pulse to acquire signal from a cylindrical volume underneath the coil. Only useful if the tissue is homogenous.

DRIVE

Philips driven equilibrium sequence.

Driven equilibrium

Use of a negative 90° RF pulse to force T_1 relaxation and shorten repetition times. Principally used to maintain a high fluid signal and to reduce scan times.

DSV

Manufacturer specification for B_0 homogeneity. It is an abbreviation for the diameter of a spherical volume, centred about the isocentre, within which changes in the magnetic field should not exceed a certain tolerance. It is therefore the optimum volume in which to image. Typical values are

< 1 ppm for 40 cm DSV. For open magnets, the corresponding value may be as much as 5 ppm.

DTI

Diffusion tensor imaging. Technique in which at least six diffusion-weighted images with different gradient combinations must be acquired to permit the calculation of the diffusion tensor (although as many as 55 are now used). Determination of the tensor permits the full realisation of the true 3-D nature of diffusion. It is a rotationally invariant measurement, i.e. unlike ADC, the values are not governed by the orientation of the structure in relation to the scanner. The tensor, once computed, can be displayed on an image as a diffusion ellipsoid. Alternatively, the dominant or preferred diffusion direction can be used to portray diffusion pathways. This is used in the brain to visualise white matter tracts and is called tractography.

Specifically, the diffusion tensor is a symmetric 3×3 matrix. The eigenvalues relate to the diffusivities along three directions given by the eigenvectors. One eigenvalue represents diffusion along the preferred or primary direction while the second and third relate to perpendicular directions.

Reference K. Arfanakis, B. P. Herman, B. P. Rogers *et al.* (2002). Diffusion tensor MRI in temporal lobe epilepsy. *Magn. Reson. Imag.*, **20**, 511–519.

See also fractional anisotropy.

Dual echo

Specific instance of a multiple echo sequence where only two separate echo images are collected. Useful for obtaining images of different contrast, for example a proton density weighted image from the early echo time and a T_2 weighted image at the later TE.

Dual tune

The ability of an RF coil that can be set to the resonant frequency of more than one nucleus, e.g. proton for imaging and some other for MRS. Associated hardware needs to be broad-band to accommodate the required frequency range (see Appendix II).

Dummy

Repetitions of the MR sequence where no data is recorded. Referred to as DDA on GE scanners (dummy data acquisition). Used for example, in single-shot sequences (e.g. in fMRI) to permit signal equilibrium (saturation) to be established.

Duty cycle

The percentage of the repetition time (TR) when the gradient is operating at the maximum amplitude. For example, in a SE sequence this may be 10%, but this increases to 50% for EPI.

DVT imaging

Deep vein thrombosis imaging. Imaging of blood clots due to the T_1 shortening of blood causing bright signal appearance on T_1-weighted images.

Dwell time

The time at the beginning of the FID during which no signal is recorded due to practical constraints.

DWI

Diffusion weighted imaging. The imaging sequence is sensitised to motion on a molecular level by using a bipolar gradient scheme with very high amplitudes (see Stejskal–Tanner). It is of clinical use in stroke: ischaemic cell swelling reduces the diffusion of water and these changes are seen earlier than with conventional MR imaging.

See also ADC and DTI.

Reference P. W. Schaefer, P. E. Grant & R. G. Gonzalez (2000). Diffusion-weighted MR imaging of the brain. *Radiology*, **217**, 331–345.

Dynamic

Repeated acquisition of images at the same slice location, usually after the administration of a contrast agent, in order to enable the time-dependent characteristics of enhancement to be fully evaluated. Also used to study physiological motion, e.g. in cardiac MRI.

Dynamic susceptibility contrast

See perfusion imaging.

Ee

Earth's magnetic field

This varies from approximately 0.3 G at the equator to 0.7 G at the poles.

See also Gauss.

ECG gating

Type of image gating or triggering from the ECG (electrocardiograph) signal. Electrodes across the chest measure changes in voltage during the cardiac cycle. The ECG is characterised by the *P–QRS–T* wave.

See also vectorcardiograph and peripheral pulse gating.

Echo modulation

All coupled spins exhibit echo modulation with multiple pulse sequences. General signal intensity equations are given for uncoupled spins only. AX systems are only weakly coupled but the signal response for strongly coupled spins (AB systems) demonstrates a modulation of signal amplitude on top of normal T_2 decay. In citrate, for example there is a fast phase change of the outer peaks with a period of approximately 135 ms. The exact nature of the signal changes depends on the sequence used, for example modulations are more pronounced with PRESS than with STEAM. There will also be different signal characteristics at high field.

Echo planar (imaging)

See EPI.

Echo spacing

The interval between each successive echo in a multiple echo train sequence, e.g. FSE or EPI.

Echo time

See TE.

Echo train length

The number of echoes in a multiple echo train, e.g. FSE or EPI sequence. Also referred to as Turbo factor.

Eddy current

Non-desirable result of rapid magnetic field changes in the gradient coils. These induce oscillating currents, and therefore magnetic fields, in the cryogen and adjacent conductors. This leads to image distortions but can be compensated by pre-emphasis or shielding.

Edge enhancement

Characteristic appearance of artificial signal 'enhancement' at the edges of tissue, which is due to motion between successive dynamic scans.

EDR

Extended dynamic range. This is a (GE) scanner setting, which increases the dynamic range of the receiver amplifier. Failure to use this may result in over-ranging and production of halo artefacts.

EEG

Electroencephalography. Measuring electrical currents in the brain to examine brain function. Poor spatial but very high temporal resolution compared to fMRI.

See also MEG.

Effective TE

The time of the central echo in the echo train of a fast spin-echo sequence. The contrast is determined by this effective value, although multiple echoes at different TEs are used.

Einthoven's triangle

The equilateral triangle position for the three electrodes used in ECG gating.

Ejection fraction

Used to assess cardiac function from cardiac MR images. Defined as a percentage value as:

$$EF = 100 \times (EDV - ESV)/EDV$$

where EDV and ESV are the end diastolic and systolic volumes, respectively as defined by manual regions-of-interest from appropriate MR images.

Elliptic centric *k*-space filling

Type of centric *k*-space filling in 3-D imaging, which also takes into account the order of the phase-encoding steps in the third dimension or 'slice' direction. Used in 3-D MRA to improve the temporal efficiency of the sequence.

Endogenous contrast

Referring to the natural differences in image contrast inherent in tissues, e.g. due to diffusion, relaxation times, etc.

See also exogenous contrast.

Endorectal coil

RF surface coil consisting of coil loop inside either an inflatable balloon or a rigid probe and inserted into the vagina or rectum.

Endorem

Iron-based contrast agent taken up in the normal liver, thereby improving the conspicuity of liver lesions.

Enhancement

Any change in signal intensity in the image caused by an *exogenous* contrast agent. On a T_2-weighted image the effect is a decrease in signal, while an increase is observed on T_1-weighted images.

Entry slice phenomenon

Synonym for in-flow enhancement.

EPI

Echo planar imaging. Sequence first proposed by P. Mansfield in 1977. Gradient intensive sequence in which combinations of the gradients are used to traverse *k*-space as fast as possible. The sequence can be single or multi-shot. Matrix size is usually limited to 64 or 128. Used whenever ultra-fast imaging is more important than quality, e.g. in paediatrics, fMRI. Commonly, blipped EPI is performed but constant and spiral trajectories are also used.

Reference P. Mansfield (1984). Real time echo planar imaging by NMR. *Br. Med. Bull.*, **40**, 187–190.

EPI factor

The number of times (or shots) that the EPI sequence has to be run in order to acquire the image data.

EPIC

The pulse programming language on GE systems.

EPR

Electron paramagnetic resonance. The magnetic resonance phenomenon observed in unpaired electrons, which occurs at much higher frequencies than with NMR.

Ernst angle

The optimal flip angle to produce the maximum signal when a reduced TR ($TR \ll T_1$) is used in gradient echo imaging. It is related to both TR and T_1 by:

$$\cos \alpha_E = \exp(-TR/T_1)$$

For $TR \gg T_1$, the optimal flip angle becomes 90°.

See also partial flip.

Eurospin test objects

Commonly used set of test objects each with a specific design and purpose.

See gel, floodfill, profile, resolution, slice warp phantom and quality assurance.

Reference R. A. Lerski & D. W. McRobbie (1992). *Eurospin II Magnetic Resonance Quality Assessment Test Objects.* Livingston: Diagnostic Sonar Ltd.

Even echo rephasing

Referring to the phenomenon where, due to the quadratic nature of phase loss by moving spins in the presence of a gradient, signal acquired at evenly spaced echoes is re-phased. (See odd-echo dephasing.) Phase loss is related by:

$$\varphi = \frac{1}{2}\gamma G v t^2$$

where φ is phase, G, gradient strength, v, velocity of motion, and t, the time interval under consideration.

Event related

Type of fMRI experiment where the stimuli are presented randomly and are of usually shorter duration than those used in a box-car experiment. Most serious fMRI research is performed in this fashion.

Excitation pulse

A radio-frequency (RF) pulse used to transmit the B_1 field in order to turn the net magnetisation towards the receiver coil for detection. If the coil is in the transverse plane, then the optimum signal is achieved with a 90° (or $\pi/2$) pulse. See Figure 21.

See also refocusing pulse.

EXCITE

The latest GE hardware platform representing the next generation in both parallel data acquisition and processing.

Exogenous contrast

Any externally administered contrast agent (usually intravenously) given to improve the differentiation of tissues within the image.

See also endogenous contrast.

Extended dynamic range

See EDR.

External interference shield

A further set of coil windings outside the shielding windings, through which current flows to counteract the effects of large moving metal objects, e.g. cars.

See B_0 inhomogeneity and proximity limits.

Ff

FADE

The fast acquisition with dual echo sequence. Picker sequence similar to DESS.

FAIR

Type of arterial spin labelling (ASL) sequence known as flow-sensitive alternating inversion recovery. A non-selective inversion pulse excites the whole volume and an image slice is recorded. Subsequently, a selective inversion is performed on the imaging slice only.

Fall time

Opposite of the rise time of a gradient waveform.

Faraday cage

The copper lining within the walls of the scan room to prevent extraneous radio-frequency sources from entering the scanner, the result of which is RF artefacts. The scan room door must be closed to maintain the integrity of the cage and usually the scanner notifies the user if the door is left open prior to scanning. See Figure 25.

Faraday's Law

An emf (electromotive force or voltage) is induced in a conductor when surrounded by a changing magnetic field. This is the basis of the eddy currents caused by the action of the gradient coils. The emf (ε) is proportional to the rate of change of the magnetic field/flux (ϕ):

$$\varepsilon = -\frac{\partial \varphi}{\partial t}$$

The negative sign is due to Lenz's law.

FAST

Fourier acquired steady state.

Fast fourier transform

The computer implementation of a fourier transformation.

Fast recovery FSE

GE driven equilibrium sequence.

Fast spin echo

See *FSE*.

Fat

Second most dominant contribution to proton MR signal. The fat peak is made up of different lipid resonances, which may need suppressing to obtain MR spectra in certain areas of the body (e.g. brain/scalp, breast). At 1.5 tesla the fat resonance is 220 Hz from water.

See also chemical shift artefact.

Fat suppression

Referring to one of the many methods of reducing the contribution of the fat signal in the image. Common techniques include CHESS, STIR, Dixon and SPIR.

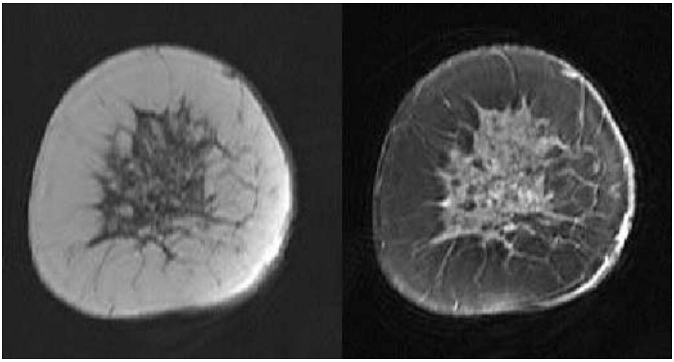


Figure 6. Breast images acquired in the coronal plane. (*left*) T_1-weighted image, and (*right*) same image with **fat suppression**.

Fat–water in phase

Imaging option for gradient-echo sequences in which the echo time is set to a field-dependent value (4.2 ms at 1.5 tesla) so that the fat and water signals are in-phase. May also be selected to be out of phase, or to be the minimum permitted value.

See also chemical shift 'of the second kind' and OOPS.

FE

Abbreviation of field-echo, an old term for gradient-echo.

Feet first entry

Entering the scanner with the head outside the magnet bore when imaging the lower body.

Ferromagnetic

Material, e.g. iron with an extremely high positive susceptibility. Magnetic field domains are induced within the object when brought close to the scanner, producing a projectile effect. Patients are screened for such objects or implants prior to examination.

FFT

See fast fourier transform.

FFT scale

Fast fourier transform scale. System setting on Siemens scanners, controlling the receiver gain.

FGRET

GE sequence, abbreviation of fast gradient echo-echo train. Combines a gradient echo with an EPI readout, to provide a high temporal resolution scan (typically 1–2 s). Predominantly used for rapid cardiac visualisation.

FID

Free induction decay. The signal produced immediately following an excitation pulse, characterised by an initial peak and a rapid decay due to T_2^* effects. The term induction arises from the current, which is induced in a coil by the rotating magnetisation. See Figure 26.

Field decay

Referring to the loss of the B_0 magnetic field due to imperfections in the superconductor, e.g. at the soldered joins.

Typically, accounts for 5–10 G loss of field per annum. In permanent and resistive magnets, factors such as ageing, temperature and power supply become important.

Field-of-view

Also known as FOV. The area being imaged. It may be symmetrical or rectangular. The FOV is related to the amplitude of the phase (G_P) and frequency (G_F) gradients as follows:

$$\gamma G_F = BW/\text{FOV}$$

$$\gamma G_p T_p = 0.5 N_p/\text{FOV}$$

where BW, N_P and T_P are the receiver bandwidth, phase encoding matrix and the duration of the phase encoding gradient, respectively.

See also off-centre FOV.

Field stability

The expected drift in centre frequency of the system. Typically, the centre frequency may vary by < 0.1 ppm/h.

FIESTA

Fast imaging employing steady state. A true refocused steady-state free precession sequence.

See true FISP.

Filling factor

The relationship between the size of the coil and the volume of tissue within the coil. The greater the percentage of the coil volume being filled by the tissue, the better the SNR.

See also coil loading.

Filter

Utilisation of some time or frequency domain filter to improve the SNR of the final image, usually at the expense of spatial resolution. Some scanners apply filters by default prior to image display and care needs to be taken to turn these off prior to making any quality assurance measurements.

Filtered back projection

Image reconstruction method used in projection reconstruction where a series of image profiles are filtered prior to back projection in order to improve the final image. Used in CT and nuclear medicine (but no longer in MRI).

First pass

Referring to the first time the contrast agent flows from the site of injection to the imaging site. Subsequent signal changes are due to the recirculation of blood. In myocardial perfusion studies this is extremely fast, requiring high temporal resolution imaging.

FISP

Fast imaging with steady-state precession. Siemens steady-state sequence using rewinding gradients in the phase encoding direction only.

See also bFFE.

Five gauss line

The proximity limit of the scanner within which entry for patients with pacemakers is precluded. Equivalent to 0.5 mT.

See also fringe field.

FLAIR

Fluid attenuated inversion recovery. Technique using a very long inversion time (TI) time (e.g. 2 s) to suppress bright fluid signal, e.g. CSF in brain.

FLASH

Siemens spoiled gradient echo sequence abbreviated from fast low angle snap shot. Rapid gradient echo sequence using a small flip angle and short TR. In turbo FLASH the *TR* is so short that T_1 contrast is maintained by using an inversion pulse. The GE equivalent is the FSPGR sequence.

Flashing artefact

Bright signal seen in the first gated image following the *R* wave (see PQRST wave) due to T_1 relaxation that has occurred in the non-imaged part of the cycle. Can be avoided by acquiring dummy data immediately after the *R* wave.

Flip angle

The resulting orientation α of the net magnetisation with respect to the B_0 field, following the application of an RF excitation pulse. It is given by:

$$\alpha = \gamma B_1 t$$

where B_1 and t is the strength and duration of the RF pulse, respectively, and γ is the gyromagnetic ratio. It can be seen that the flip angle is related to SAR (RF power).

Floodfill phantom

Large homogenous phantom designed to enable signal-to-noise and uniformity measurements to be taken.

See also quality assurance.

Flow artefacts

Image artefacts specifically caused by flowing spins or in particular vascular flow. A common problem is ghosting in the phase-encoding direction, which is most apparent when the blood flow is perpendicular to the imaging plane. Also, an apparent lateral displacement of vessels may occur in even-echo rephasing, where the vessel is in the imaging plane but has an oblique orientation to the frequency-encoding direction.

Flow compensation

Technique incorporating additional gradients (sometimes called FLAG or flow adjusted gradient waveforms) to reduce intravoxel dephasing. This improves the uniformity of blood signal and reduces CSF flow effects, etc.

See also gradient-moment nulling.

Flow phenomena

Flowing blood can result in either a signal loss or an increase in MRI. Flow can be characterised as laminar, where the flow has a parabolic profile with the highest velocities at the centre of the vessel, or turbulent where the profile is flat towards the centre. The onset of turbulent flow is predicted from the

Reynolds number. In-flow enhancement causes flowing blood to appear bright. Signal voids are caused by high velocity signal loss and also dephasing due to motion along a gradient (see even-echo rephasing).

Flow void

Signal loss due to the motion of (usually) blood and taken advantage of in black blood angiography.

Fluorine

^{19}F is the MR visible isotope of fluorine, which has the second highest sensitivity of all nuclei. Virtually absent in the human body, it is extremely useful in monitoring fluorinated drugs, e.g. 5FU or gemcitabin in chemotherapy.

fMRI

Functional MRI (brain), note the 'f' is lower-case by convention. A non-invasive method of studying brain function. A commonly used technique is BOLD. It permits the visualisation of areas of the brain, which have responded to a specific task or stimulus. Used generally in the research of cognition but also being used increasingly for surgical and radiotherapy planning.

Reference P. Gowland, S. Francis, P. Morris & R. Bowtell (2002). Watching the brain at work. *Phys. World*, **15**(12), 31–35.

Foldover

Alternative term (used by Philips) for aliasing or phase wrap.

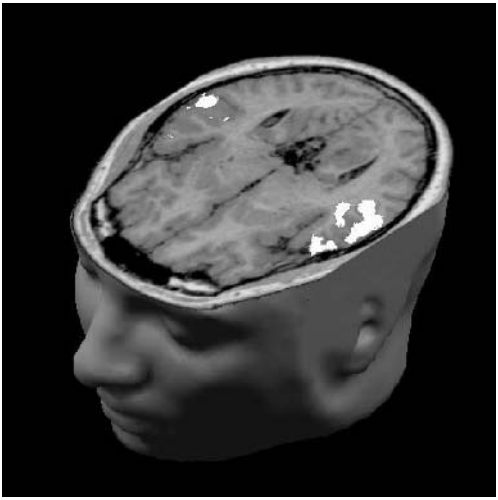


Figure 7. Here the activation detected in a **fMRI** examination is overlaid onto a 3-D surface rendering. Pixels that correlate significantly with the stimulus are highlighted by computer software (in white). In this case the temporal lobe has responded to an auditory test.

Foldover suppression

See no phase wrap.

Footprint

The siting requirement of the scanner determined by the extent of the fringe field. Typically, may be as small as 35 m^2 for modern actively shielded designs.

Fourier transform

Mathematical algorithm in which time-varying signals can be decomposed into a series of sinusoidal components of varying frequency ω, phase ϕ and amplitude a. The process by which the recorded MR signal is decoded into an image.

The fourier transform of $S(t)$ is given by:

$$S(t) = a_0 + a_1 \sin(\omega_1 t + \varphi_1) + a_2 \sin(\omega_2 t + \varphi_2) + \cdots$$

See Appendix V for some common fourier pairs.

Fractional anisotropy

Dimensionless quantity, which is a measure of the directional dependence of diffusion in each image voxel. It is a scalar quantity derived from the diffusion tensor and is given by:

$$\mathrm{FA} = \sqrt{\frac{1}{2}}\,\frac{\sqrt{\left((\lambda_1 - \lambda_2)^2 + (\lambda_2 - \lambda_3)^2 + (\lambda_3 - \lambda_1)^2\right)}}{\sqrt{\lambda_1^2 + \lambda_2^2 + \lambda_3^2}}$$

Where $\lambda_1 \ldots \lambda_3$ are the eigenvalues from the diffusion tensor. FA has values ranging from 0 (perfectly isotropic, equal to a spherical diffusion path) to 1 (when $\lambda_1 \gg \lambda_2 = \lambda_3$, equal to a cylindrical diffusion path). FA values of 0.1 have been reported in brain tumours and 0.5 in normal white matter. A related but different measure is the relative anisotropy (RA), which is the ratio of anisotropic to the isotropic part of the diffusion tensor.

See also DTI.

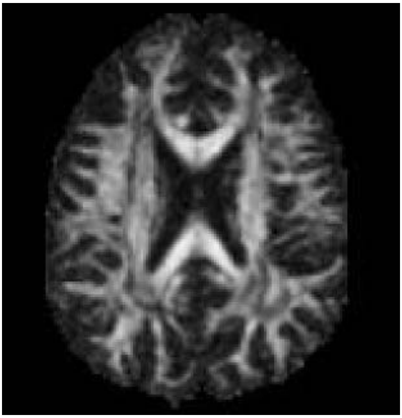


Figure 8. Fractional anisotropy map depicts the white matter tracts in the brain. (Courtesy of D. K. Jones, NIH.)

Fractional echo

See partial echo.

Fractional NEX

See partial fourier.

Frame of reference

See rotating or laboratory frame.

Free induction decay

See FID.

Free protons

Water molecules with high tumbling rates and short correlation times (e.g. bladder urine, CSF). The opposite of bound protons (there are also intermediate or 'structured protons').

Frequency encoding

Use of a gradient to induce linear changes in resonant frequency, which varies with distance so that the signal may be encoded spatially. Unlike phase encoding, it is done only once, at the time of the echo measurement. Note the dephasing lobe of this gradient (See Figure 21) to ensure no phase loss at the time of the echo. Chemical shift artefact is observed in this encoding direction.

Frequency wrap

Aliasing that occurs in the frequency encoding direction. This is seldom a problem as the use of filters and rapid sampling (at the Nyquist frequency) ensures that wrap does not occur in the frequency direction.

See also phase wrap.

Fringe field

The magnetic field produced by the scanner, which extends beyond the scan room (or more specifically outside the imaging volume). Reduced by active shielding. The fringe field drops off quickly at a distance, r, from the magnet as:

$$B_{\mathrm{FF}} \propto B_o / r^3$$

The fringe field has both axial (z-direction) and radial (x,y)-components. Typically, the axial fringe field will be greater than the radial field at any given distance. For a modern (closed bore) scanner, it is approximately 1.6 times greater, for example 2.5 m radial and 4.0 m axial.

See also five gauss line and proximity limits.

FSE

Fast spin echo. Uses multiple 180° refocusing pulses with different phase encoding steps (unlike multiple spin-echo). It is used predominantly to produce fast T_2-weighted (but also T_1) images. Multiple echoes are used to obtain an image rapidly with an effective TE equal to the central echo. The speed-up factor is given by the echo train length, which must be conservatively used (typically 16 or 32) to prevent image blurring. GE also offers FSE–XL, which is an enhanced sequence with features such as blurring cancellation.

Reference J. Listeraud, S. Einstein, E. Outwater & H. Y. Kressel (1992). First principles of fast spin echo. *Magn. Reson. Quart.*, **8**, 199–244.

FSPGR

GE sequence, abbreviated from fast spoiled gradient echo. A rapid gradient-echo sequence utilising spoiling. The Philips version of this sequence is called FLASH.

FT

Fourier transformation.

Functional MRI

Referring generally to any advanced MR method that permits the examination of function rather than anatomy, e.g. perfusion, diffusion, MRS.

When applied to the brain, fMRI specifically refers to techniques for evaluating cortical activity.

Fusion

See registration.

FWHM

The full width at half maximum height. A measure of peak width (linewidth), and indication of shim quality. In MRS, desirable values are < 7 Hz for single voxel, 10–12 Hz for 2-D and < 15 Hz for 3-D CSI.

How safe is MRI?

To put this into historical context, in 1980 the safe static field limit was thought to be 0.35 tesla. Today, there are no known long-term biological effects associated with exposure of up to 10 tesla. However, as field strength increases, effects such as SAR, gradient stimulation and acoustic noise become more of an issue. The most obvious safety concern is the projectile effect of the scanner. There has only ever been one reported death due to projectile incidents and this occurred in 2001.

Gg

G/cm

Unit of magnetic field gradient (gauss per centimetre).

See mT/m.

Gadodiamide

See Omniscan.

Gadolinium

Paramagnetic ion widely used as an exogenous MR contrast agent. Must be chelated to some other molecule to reduce toxicity (e.g. DTPA). This reduces the relaxivity of the Gd^{3+} ion, from approximately 10 $mM^{-1}\ s^{-1}$, to half this value.

See also Gd-DTPA and relaxivity.

Gamma

Greek symbol (γ) used to represent the gyromagnetic ratio.

Gating

Referring to the synchronisation of the pulse sequence to some periodicity, for example the cardiac cycle or respiratory motion. Cardiac gating is performed by measuring either the ECG or peripheral pulse. Used to reduce artefacts caused by motion but at the expense of increased imaging time.

Gauss

Unit of magnetic field, where 1 tesla (T) = 10 000 gauss (G). Magnetic field, is measured with a gaussmeter. A hand-held probe may be used (calibrated in a zero gauss screened chamber) to measure fringe field.

See Earth's magnetic field.

Gaussian

Bell-shaped filter used in apodisation. A normal (or Gaussian) distribution is characterised by 65% of the data lying within one standard deviation of the mean. Gaussian noise refers to a 'normal' distribution of noise.

Gd-DTPA

Common MRI contrast agent. Longest safety record of all the agents in use. Consists of Gd chelated to three diethylene triaminepentaacetic acid (DTPA), producing a linear ionic complex with a −2 charge. It is balanced chemically with two meglumine charges. (See Appendix VI). The resulting agent is called dimeglumine gadopentetate but is marketed as Magnevist.

See also relaxivity.

Reference K. L. Nelson, L. M. Gifford, C. Lauber-Huber *et al.* (1995). Clinical safety of dimeglumine gadopentetate. *Radiology*, **196**, 439–443.

Gd-DOTA

An ionic gadolinium based contrast agent. Gd is chelated to tetraaza-cyclododecane-tertraacetic acid (DOTA) to form a cyclic molecule. The resulting agent is called gadoterate, and is marketed as Dotarem (Guerbet).

See also Prohance.

Gel phantom

Set of (Eurospin) test objects used to investigate relaxation time measurement accuracy and image weighting. They consist of a set of test tubes filled with agarose gel doped with varying amounts of gadolinium to give a characteristic range of relaxation times.

Specific types of gel phantoms are also used in MR dosimetry.

See also quality assurance, test object.

Geometric distortion

Specific measure of distortion related to the change in image to object shape. A suitable phantom comprising a grid arrangement of known dimensions may be used to assess this. Measurements of three distances across the phantom are taken and the percentage ratio of the SD to the mean of these measurements is recorded. The acceptable tolerance is $\pm$ 0.6%.

See also linearity.

Reference R. Lerski, J. De Wilde, D. Boyce & J. Ridgeway (1998). Quality control in magnetic resonance imaging, *IPEM Report no. 80.*

Ghosting

A diffuse or discrete signal appearance usually caused by patient movement during the scan. Owing to the discrepancy

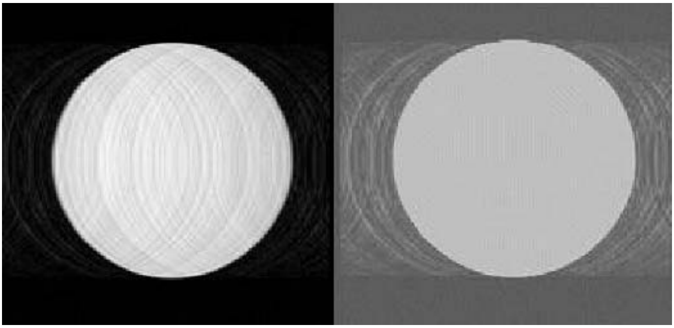


Figure 9. Motion of this test object during scanning has created characteristic **ghosting** in the phase-encoding direction.

in the length of time required for phase and frequency encoding, it is usually only observed in the phase direction. Usually non-periodic motion (coughing, etc.) causes a smeared appearance while periodic motion (e.g. breathing) appears more discrete. It also may be caused by system instability and should be checked as part of quality assurance of the scanner. It can be measured in the phase encoding direction of the image background and expressed as a percentage of the main phantom signal. Acceptable levels are <1% for conventional sequences, rising to 5% for EPI.

See also quality assurance and gating.

Gibbs artefact

Presence of multiple lines near a high contrast interface caused by undersampling of data. Commonly seen in the C-spine. Can be reduced by increasing the matrix size in a

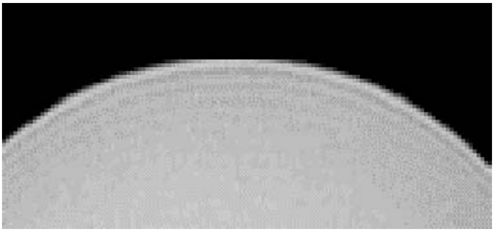


Figure 10. Here Gibbs artefact or ringing is seen as discontinuous lines at the edge of this test object.

given direction. It is also referred to as truncation artefact or ringing.

Gibbs overshoot

The oscillations at the edge of a square waveform caused by the finite number of Fourier harmonics used in its representation. It is the cause of Gibbs artefact in MR images.

Glx

Notation used in ^{1}H spectra to indicate the combined peaks of glutamate and glutamine, which are not readily resolved at field strengths of less than 3.0 tesla. Peaks occur at 2–2.4 and 3.6–3.8 ppm.

Golay coils

Design of gradient coil consisting of a set of four coils lying along the scanner bore to produce the transverse gradients (G_x and G_y), i.e. a linear field change in a direction perpendicular to the B_0.

See also Maxwell pair.

Gradient

A (linear) change in magnetic field. The application of a gradient results in a change of both phase and frequency and is used to encode MR image data spatially. First proposed by Lauterbur as a method of encoding an image. Gradient specifications are given in terms of peak amplitude and rise times, or as a combined slew rate. Typical gradient amplitudes are 10–50 mT/m. The gradients are produced by specialised coils inside the scanner (Maxwell pair, Golay coils). They must be shielded to prevent eddy current problems.

Reference P. C. Lauterbur (1973). Image formation by induced local interactions: examples employing nuclear magnetic resonance. *Nature*, **242**, 190–191.

Gradient echo

Type of signal echo created by the application of a gradient reversal. The absence of a 180° refocusing pulse results in the signal being T_2^* weighted and prone to susceptibility artefacts.

Signal is given by (note this is for a spoiled gradient echo):

$$S \propto \frac{\sin\alpha\left(1 - \exp\left(-\mathrm{TR}/T_1\right)\right)\exp\left(-\mathrm{TE}/T_2^*\right)}{1 - \cos\alpha\exp(-\mathrm{TR}/T_1)}$$

where α is the flip angle.

See also partial flip angle.

Gradient moment nulling

Reduction of flow effects by using gradients to ensure signal is re-phased appropriately. Also known as motion artefact suppression technique or MAST.

See even echo rephasing and flow compensation.

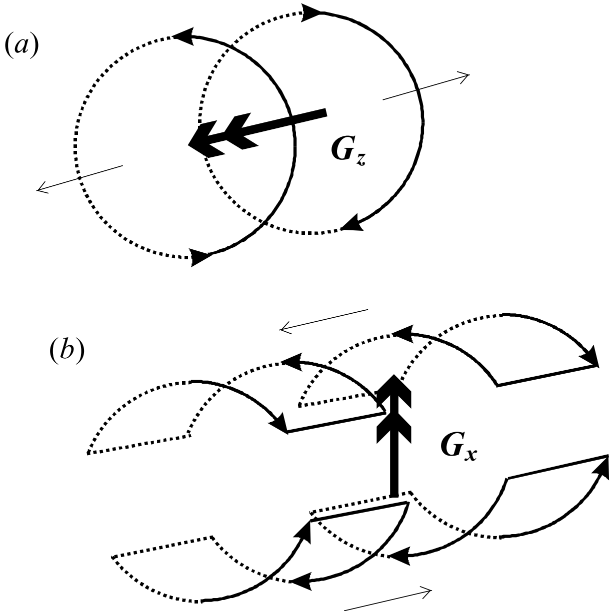


Figure 11. **Gradient coils**. (*a*) A **Maxwell pair** produces the gradient parallel to B_0 (G_z). (*b*) A set of **Golay coils** produce a transverse gradient G_x and a second set orientated at 90° produces G_y (not shown). In each diagram, the current direction is indicated by the solid arrow, magnetic field by the thin arrow and the gradient by the double arrowhead.

GRAPPA

Siemens implementation of parallel imaging. Stands for generalised autocalibrating partially parallel acquisition.

Reference M. A. Griswold, P. M. Jakob, R. M. Heidemann *et al.* (2002). A generalised autocalibrating partially parallel acquisitions (GRAPPA). *Magn. Reson. Med.*, **47**, 1202–1210.

GRASS

Gradient recalled acquisition in steady state. GE sequence.

See also steady state.

Gyromagnetic ratio

Property of a nucleus determined by its mass and charge. It is the constant in the Larmor equation (denoted as γ), and is also referred to as the magnetogyric ratio. Hydrogen has a value of 42.58 MHz/T. See Appendix II.

Greyscale

The normal image representation of pixel intensities. A colour map is assigned to the image data with 0 set to black and the maximum value set to white (e.g. 255 for 8-bit data), and all other values assigned intermediate shades of grey. For an inverse image the opposite scale is used. A colourscale image may contain any user-defined colours or shades (e.g. 'hot iron'-a yellow/orange scale is often used in fMRI to display activated pixels). Often parameter maps are shown in colour and overlaid onto original greyscale images.

G_z (G_x, G_y)

Notation to indicate a gradient in the *z*-direction (or *x*,*y*). A Maxwell pair is used to produce G_z and two sets of Golay coils are used for G_x and G_y. This is shown in Figure 11. The gradients are turned on in a specific order (Figure 21).

Hh

$\hbar$ 'bar'

Planck's constant divided by 2π (see Appendix I). Related to the energy difference between spin states in an external magnetic field. Written as $\hbar$.

Haemodynamic lag

The observed delay between actual neuronal activation and the time taken for increased oxygen demand as detected by BOLD fMRI. This is of the order of several seconds.

Hahn echo

A particular spin echo sequence where the excitation and refocusing flip angles differ from the optimum 90° and 180°. The reduced signal is related to the two flip angles by:

$$\sin\alpha_1 \ \sin^2(\alpha_2/2)$$

Reference E. L. Hahn (1950). Spin echoes. *Phys. Rev.*, **80**, 589–594.

Half echo

See partial echo.

Half scan

See partial fourier.

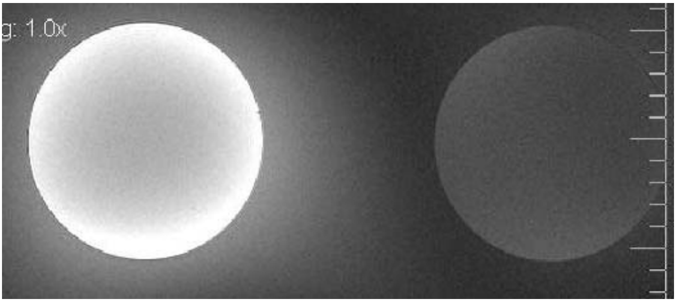


Figure 12. **Halo artefact** seen here in a phantom image. (Courtesy of M. Graves, Addenbrooke's Hospital, Cambridge.)

Halo artefact

Strange appearance where the signal at the centre of the image is lost. The image appears 'washed out' with an outer bright background. Occurs due to the receiver gain being incorrectly set (over-ranging) and the signal being truncated.

Hanning filter

Symmetrical shaped function with high values at the centre and a cosine-shaped roll-off, used as a low pass spatial domain filter. It is given by:

$$H(x) = 0.5 + 0.5(\cos 2\pi x/I)$$

where I is the width of the Hanning window (smaller values cause a sharper roll-off).

See also low-pass and high-pass filter.

Harmony
Siemens 1.0 Tesla scanner model. (Also Symphony and Sonata at 1.5 tesla).

HASTE
Half-fourier single shot turbo spin echo sequence. A FSE technique in which only half of *k*-space is acquired thereby improving image speed.

see also partial *k*-space.

Head coil
RF transceiver coil used in the imaging of head/brain anatomy. Usually of a birdcage design.

Head first entry
Method of entry into the scanner for imaging the head and upper torso.

See also feet first.

Header
The first part of the image file, which is concerned with patient, scan and file format information rather than the signal intensity values. The header will be either a fixed length or contain the start position of the image data within it.

See DICOM.

Helium
Used in liquid form as the cryogen for the superconducting scanner. The isotope ^{3}He may also be used as a hyperpolarised gas for ventilation (lung) imaging.

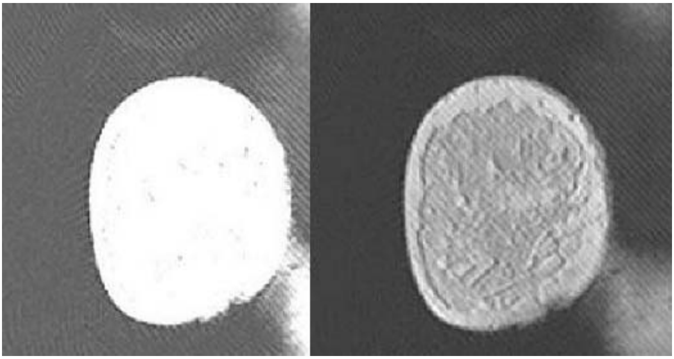


Figure 13. Herringbone artefact demonstrating a typical criss-cross pattern on top of this breast image.

Helmholtz pair

Pair of coils with a separation distance equal to their radius, producing a very uniform magnetic field.

See also solenoid.

Hermitian

Referring to the diagonal (or conjugate) symmetry in *k*-space.

Herringbone artefact

Characteristic criss-cross pattern appearance in the image due to a data reconstruction error. The corruption in the image is present in every pixel due to the nature of *k*-space.

Hertz

Unit of frequency, 1 hertz (Hz) is equal to 1 cycle per s (s^{-1}).

Figure 14. **High Field MRI.** Photograph of the new whole-body capable 3.0 tesla scanner being installed at the Centre for MR Investigations at Hull Royal Infirmary, England, one of the first of its type in the UK.

High field

Any field strength above 1.5 tesla. Currently clinical scanners are limited to 3.0 T, although research scanners operate at fields up to 11 T.

High order phase

Referring to the high amplitude phase encoding steps that correspond with the data at the edges of *k*-space or the image detail.

High pass filtering

Removing low frequency components from MR data. In MRS, it may be used to remove residual water from a spectrum, preserving the higher frequency metabolites. The filter consists of the value 1 above a certain frequency threshold and zero elsewhere.

See also low pass filtering.

High velocity signal loss

Phenomenon of flowing blood in a spin-echo sequence, used as an MRA technique. Blood appears dark (black-blood) as it moves out of the imaging slice between the 90° and 180° RF pulses, so that the signal is not measured. The velocity v needed to exit the slice and produce maximum signal loss, is given by:

$$v > d/(\mathrm{TE}/2)$$

where d is slice thickness.

Homogeneity

Refers to how uniform the magnetic field is. Typical values for the main magnetic field are < 1 ppm in a 40 cm DSV (i.e. less than 1 Hz frequency variation in 10^6). Variation in B_1 field leads to incorrect flip angles and signal variation across the image. This is particularly prominent in surface coil imaging with large signal drop across the image.

Hyperechoes

Use of a symmetrical distribution of equally spaced reduced flip angle pulses either side of a 180° pulse (i.e. α_1 and $-\alpha_1$).

The contribution of stimulated echo components in the hyperecho formation provides increased signal intensity over that obtained from a conventional multiple echo train sequence. The use of reduced flip angles makes the sequence less SAR intensive compared to conventional FSE sequences and is useful at high field.

Reference J. Hennig & K. Scheffler (2001). *Magn. Reson. Med.*, **46**, 6–12.

Hyperintense

Description of signal intensity that is brighter than surrounding tissue. See Figure 30.

See also hypointense and isointense.

Hyperpolarised gas imaging

The use of a laser-polarised noble gas (e.g. xenon, helium) in lung ventilation imaging. The normally weak signal is improved by hyperpolarising the magnetisation using optical pumping techniques, which increases the signal by a factor of 100 000. This increase is sufficient for the gas itself to be imaged. In addition, xenon dissolves in the blood and can be used in combined ventilation/perfusion studies.

Reference M. S. Albert, G. D. Cates, B. Driehuys *et al.* (1994). Biological magnetic resonance imaging using hyperpolarized ^{129}Xe. *Nature*, **470**, 199–201.

Hypointense

Description of signal intensity that is darker than surrounding tissue. See Figure 30.

See also hyperintense and isointense.

Hypoxia

Cellular oxygen deficiency. Important in MR cancer studies as hypoxic tumours have an increased resistance to radiotherapy and chemotherapy and are also more likely to metastasise. The gold standard method of measurement is via oxygen partial pressure using an Eppendorf electrode, which involves inserting a needle into the tumour site. MR alternatives include spectroscopy (detection of lactate), contrast enhancement (perfusion) and R_2^* mapping.

Who invented MRI?

There are quite a few people who can lay claim to its invention. In 1946 two scientists, Bloch and Purcell, demonstrated independently the nuclear magnetic resonance effect in bulk matter and NMR – as it was then called – was born. The technique was mainly used as a spectroscopy tool until 1972 when Lauterbur's application of magnetic gradients produced the first MR image – two test tubes of water. In another huge leap forward, Mansfield in 1976, using slice selection and fourier-encoding techniques, produced the very first in vivo human image of his own finger. By the early 1980s, Oxford Magnets were producing whole-body scanners, and a new medical imaging modality was realised. Today, over 20 million MRI examinations are performed worldwide each year. In 2003, Lauterbur and Mansfield were awarded the Nobel Prize for their contribution to the field.

IAMS

Internal auditory meatus. Small canal through the temporal lobe containing facial and auditory nerves.

iDRIVE

GE platform using state-of-the art gradient and reconstruction speed to image in real-time. Useful for localising the short axis of the heart and studying physiological motion, e.g. swallowing.

Imaginary

The non-real part of a complex number. One component of signal from a quadrature coil, usually denoted as Q (quadrature).

Imaging, 2-D

The standard method of image acquisition. Utilises slice selection to acquire multiple planar images. Typically, the in-plane spatial resolution is 1 mm or better. The through-plane (slice) resolution is usually limited to about 2–5 mm. Images may still be reformatted and displayed in 3-D, although best results are obtained with thin contiguous slices.

See also phase encoding and frequency encoding.

Imaging, 3-D

Volume image acquisition whereby a volume or slab is acquired and this is then subdivided into thin sections using phase encoding in the 'slice' direction. This method has the advantage over multiple 2-D imaging in improved through-plane resolution, usually of the order of 1–2 mm. This provides more isotropic images which can be reformatted or displayed in three dimensions with good quality.

In addition, signal-to-noise (see SNR) improves by a factor of $\sqrt{N}$ where N is the number of phase encoding steps in the slice direction. The penalty is increased scan time, which increases by a factor of N.

Phase wrap occurs additionally in the slice direction and needs to be accounted for: some scanners acquire more images than actually prescribed in this direction to stop the wrap affecting the designated volume.

Impedance matching

Ensuring that the electrical impedance (resistance, inductance and capacitance) of the coil is commensurate with ancillary electronic components. This ensures that RF energy is transferred efficiently between the system and the coil.

iMRI

Interventional MRI (note the lower-case 'i' by convention). Referring to any MR examination where hardware (e.g. RF coils or the magnet bore) is designed specifically to permit some interventional procedure while the patient remains either in the scanner or outside the scanner but still on the patient bed.

See also open scanners.

Infarct penumbra

Circumferential region at the edges of the reduced diffusion area in stroke, which may still be viable and demonstrates normal perfusion characteristics.

See also perfusion imaging.

Inferior

The conventional direction of the patient's feet. It is the bottom of a sagittal and coronal image (see Figure 2).

See also superior.

In-flow enhancement

Also known as flow-related enhancement. Phenomenon of flowing blood entering the imaging slice in gradient echo imaging, making it appear bright. Repeated RF pulses saturate stationary spins, whereas 'fresh' spins entering the slice are fully magnetised and appear bright. In multi-slice imaging the first slice demonstrates the greatest enhancement (leading to the alternative name of entry-slice phenomenon). The effect is reduced as slice thickness is increased, but this can be overcome by using a variable flip angle across the imaging slice (e.g. TONE). For maximum enhancement the spins in a slice of thickness d are replaced in-between successive RF pulses during the repetition time TR, and so have a velocity equal to d/TR.

Infusion pumps

A device for the automatic delivery of contrast agents ensuring a reproducible bolus dose. The volume and rate of delivery can be set, and the device may be operated from inside the control room.

Inorganic phosphate

Spectral peak seen at 5 ppm in phosphorus MRS. The change in its chemical shift can be used to calculate pH from the Henderson–Hasselbach equation. See Figure 20.

Intera

Name of the current Philips scanner model. The previous model was called Gyroscan.

Interleaved

The acquisition of 'odd' numbered slices followed by 'even' numbered slices as a method of eliminating cross-excitation.

Also used in dynamic scanning to describe non-sequential imaging where slices are acquired in turn.

Interpolatation

Estimating an intermediate value from a discrete set of data points. Specifically, Image interpolation refers to the process of increasing an image matrix and filling in the missing data by using some function to estimate values from the adjacent rows and columns. The opposite process is decimation.

Interventional device

MR compatible device, which permits an MR-guided interventional procedure to be performed (e.g. a biopsy). The device should consist of fiducial markers, which are visible on MRI and subsequently enable the localisation of a tumour.

Reference G. P. Liney, D. J. Tozer, H. Brunsveld Van Hulten *et al.* (2000). Bilateral open breast coil and compatible intervention device. *J. Magn. Reson. Imag.*, **12**, 984–990.

Inverse lateralisation

Referring to the activation observed in motor and sensory fMRI experiments that appears in the opposite hemisphere to the side of the body being tested (i.e. left motor cortex responds to right-hand motion).

Inversion recovery

The use of an excitation pulse of 180° to invert spins. Used in STIR, FLAIR, or any other inversion prepared sequence.

The inversion recovery sequence can be used to measure T_1. The signal is measured for different values of inversion time, TI and T_1 calculated from:

$$S \propto \left[1 - 2\exp(-\mathrm{TI}/T_1) + \exp(-(\mathrm{TR} - \mathrm{TI})/T_1)\right]$$

Several repeat experiments should be made covering the range of the expected T_1 making it a lengthy process.

See also null-point and bounce-point artefact.

Inversion time

See TI and inversion recovery.

Inverse image

Displaying the image in an inverted greyscale i.e. black for highest values, white lowest. Useful for comparing MRA results with conventional DSA (digital subtraction angiography).

IPA

The Siemens system of integrated panoramic arrays. The ability of various RF coils which can be connected and used together (up to 4 CP or circularly polarised coils).

IR

Inversion recovery, used as a prefix in sequences to indicate that these are inversion prepared, i.e. begin with the magnetisation along the negative *z*-direction.

Ischemia

Insufficient blood to a particular organ. Leads to stroke and can be readily imaged by diffusion weighted MRI.

ISIS

Image selected in vivo spectroscopy. Method of spectroscopy localisation that requires combinations of non-selective and selective inversion pulses, which are then algebraically combined to obtain the desired signal.

Isocentre

The centre of magnet, which, by definition, is the most homogeneous part, and the place to which the patient is landmarked prior to scanning. Each time images at different locations are prescribed, the patient is automatically repositioned to the isocentre.

See also DSV.

Isochromat

Said of spins with the same frequency of precession (literally means same colour).

Isointense

Signal, which is the same intensity as surrounding tissue.

see also hypointense and hyperintense.

Isotropic

Referring to spatial resolution that is equivalent in all three directions. Crucial for good reformatting of data in any plane and 3-D reconstructions.

Also used to describe diffusion, which is unrestricted, and therefore the same magnitude in each direction.

Chemical shift artefact: how large is it?

The magnitude of the fat–water shift artefact can be determined by knowing the receiver bandwidth, the number of pixels in the frequency-encoding direction and the inherent difference between fat and water resonance, which at 1.5 tesla is equal to 220 Hz.

Take a bandwidth of ±16 kHz and a matrix of 256: there are a total of 32 000 Hz difference across the dimension of the image. This means that each pixel can accommodate only 125 Hz (=32 000/256) and so there is nearly a 2-pixel spread of fat and water.

Jj

J-coupling

The phenomenon of spin–spin interaction mediated via covalent bonds (usually the nearest), which leads to splitting of spectral peaks. Also known as indirect or scalar coupling. The magnitude of the effect is given by the coupling constant *J* and molecules are subdivided into AX or AB systems.

See also TE averaging.

J-modulation

See echo modulation.

What is the ideal clinical field strength?

3.0 tesla has already demonstrated advantages in terms of musculoskeletal imaging, fat suppression and brain imaging. However, current lack of RF body coils may limit its use as the whole-body field strength of choice. Economically, it may be argued that the purchase of several clinically proven 1.5 T scanners may be a better option. The question remains controversial until the full utilisation of 3.0 tesla can be demonstrated for all anatomical regions.

Kk

Kaplan–Meier plot

An often used step-wise plot demonstrating patient survival following a given intervention or treatment. The *y*-axis shows the proportion of surviving patients and the *x*-axis gives the survival time.

Reference B. S. Everitt (2003). *Medical Statistics from A to Z*, Cambridge: Cambridge University Press.

Key hole imaging

A dynamic scan where only the central part of *k*-space is acquired to speed up imaging time and improve the temporal resolution. Image detail is 'filled in' from an earlier scan in which the whole of *k*-space has been recorded. Works well when only bulk signal contrast changes from image to image, e.g. in a dynamic contrast-enhanced scan.

Reference J. J. Van Vaals, M. E. Brummer, W. T. Dixon *et al.* (1993). Keyhole method for imaging of contrast uptake. *J. Magn. Reson. Imag.*, **3**, 671–675.

k-space

An array of numbers whose fourier transform is the MR image. Each element in *k*-space contains information about every image pixel. The faster *k*-space can be filled, the quicker the image acquisition. Many techniques are available for only partially filling *k*-space; however, image quality is degraded.

The order in which k-space is filled may also be altered. This is related to low and high order phase. k is given by:

$$k = \gamma G t$$

where G is the amplitude of the encoding gradient and t is the duration of this gradient (Gt is the 'area under the gradient').

The maximum value of k (k_{max}) is the reciprocal of pixel size, and the k-space sampling size (Δk) is the reciprocal of the FOV.

See also partial k-space, k-space trajectory and conjugate symmetry.

Reference R. Mezrich (1995). Perspective on k-space (tutorial). *Radiology*, **195**, 297–315.

k-space ordering

The order in which k-space is filled, i.e. whether the high or low phase orders are acquired first. This may be sequential, centric or concentric.

k-space path

See k-space trajectory.

k-space shutter

Partial k-space technique in which the outer lines of k-space are not acquired in order to speed up imaging time.

k-space trajectory

Referring to the direction in which k-space is traversed (i.e. how the gradient encoding is performed). The more efficiently this is done, the faster the image can be recorded. The

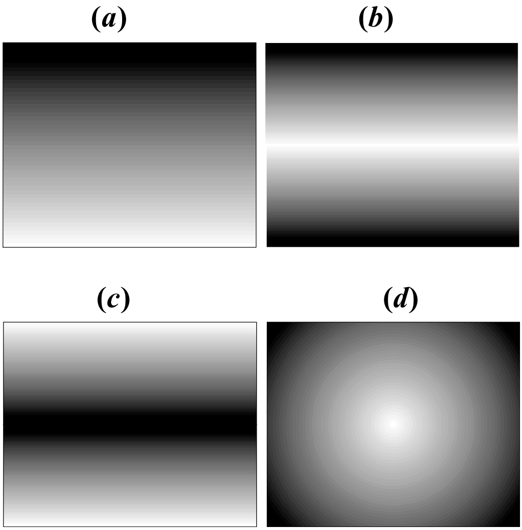


Figure 15. ***k*-space ordering and trajectory. In normal sequences *k*-space is filled in a linear line-by-line manner, although the order in which it is filled may be altered, e.g. (*a*) sequential, (*b*) centric and (*c*) concentric. Certain sequences use more efficient filling strategies and use complicated *k*-space trajectories, for example (*d*) spiral *k*-space.**

simplest method acquires *k*-space line-by-line (linear), although the ordering may be changed (e.g. centric *k*-space). More complicated approaches use spiral trajectories (see also PROPELLER). See Figure 15.

K^{TRANS}

Transfer constant. A parameter used in pharmacokinetic modelling to describe the exchange of contrast agent between the blood plasma and the extracellular extravascular space. Other parameters include V_e, the volume of extravascular extracellular space, and K_{ep} or the rate constant, defined as K^{TRANS}/V_e. When the contrast delivery to the tissue is sufficient, the transfer constant is equal to the capillary permeability surface area product. See Figure 19.

Reference P. S. Tofts, G. Brix *et al.* (1999). Estimating kinetic parameters from dynamic contrast-enhanced T_1-weighted MRI of a diffusible tracer: standardised quantities and symbols. *JMRI*, **10**, 223–232.

MR scanner history

The first whole-body MR scanner was built in 1979 and was a resistive type. While easier to construct, use of this type has been restricted to low field. A year later, a whole-body superconducting system was designed. However, it was not until 1989 that an actively shielded system was built – the forerunner of all hospital scanners in use today. In 1997, actively shielded systems at 3.0 tesla were being introduced. Modern high-field scanners can be built with a wide short bore design (typically 1.6 m in length and 60 cm diameter). Compare this to a 4 tesla system in 1987, which was only 45 cm wide and 4 m long! (incidentally it had a boil-off rate of 1.5 l/h helium and 5 l/h nitrogen – quite an expense!)

Laboratory frame

Frame of reference whereby spins precess at the Larmor frequency from the observer's point of view. Compare this with the rotating frame of reference.

Lactate

Important metabolite in proton MRS that is related to the end product of anaerobic metabolism. It appears as a doublet and is further characterised by being inverted at an echo time of 135 ms. Its resonance is at 1.33 ppm and may be obscured by lipids.

Larmor frequency

The precessional or resonant frequency (ω_0) of spins when they are placed in an external magnetic field. It is related to the magnetic field B_0 by the Larmor equation:

$$\omega_0 = \gamma B_0$$

where γ is the gyromagnetic ratio. The above frequency is in radians per second. Conventionally written (although wrongly) without the negative sign.

See also precession.

LAVA

Low angle volume acquisition-GEs inversion recovery prepared 3-D sequence for dynamic imaging of volumes.

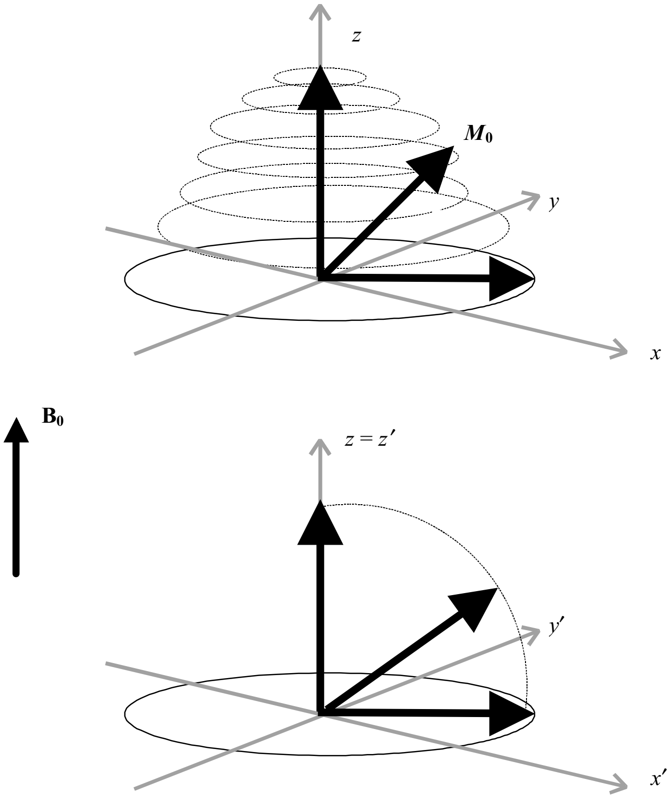


Figure 16. (*Top*) In the laboratory frame of reference the B_1 field is applied at 90° and at resonance (i.e. oscillating with the spins) to produce a spiralling motion of the net magnetisation vector towards the transverse plane. (*Bottom*) By adopting a rotating frame of reference (indicated by the co-ordinate system x', y', z' with the x-y axes rotating at the larmor frequency) B_1 appears fixed, and the motion is a simple tip or rotation into the transverse plane.

Lenz's law

Related to the negative sign in Faraday's law. The induced current acts in the sense that its magnetic field opposes the change producing it.

Level

Referring to the intensity level of the image display. See windowing.

LC model

MRS processing algorithm. See peak area.

Linearity

Change in the image dimensions due to distortion. More specifically it refers to the absolute difference between the mean of (at least) three measurements taken across the dimensions of a suitable phantom from the true value. Acceptable tolerance is typically 1 mm (for a distance of 120 mm*).

See also geometric distortion.

Reference *R. Lerski, J. De Wilde, D. Boyce & J. Ridgeway (1998). Quality control in magnetic resonance imaging. *IPEM Report no. 80.*

Linear regression

Used to investigate the relationship between two groups of variables. More specifically it is used to predict one variable from the other.

Linearly polarised

The simplest form of non-quadrature RF coils.

Linewidth

A measure of the spectral peak width, giving an indication of shim quality. See FWHM. Narrow linewidths enable closely spaced peaks to be discriminated. The linewidth is inversely proportional to T_2^*. Also specifies the width of the spectral filter used in apodisation.

Lipids

A number of proton metabolite peaks from fatty tissue. Composed of methylene (CH_2) protons at 1.3 ppm and methyl (CH_3) protons at 0.9 ppm. There are also peaks at 2.2 ppm and 5 ppm (from unsaturated lipids). The dominant peak at 1.3 ppm may need suppressing in certain regions (e.g. breast) in order to observe metabolites at smaller concentrations.

Liver-specific contrast agents

Iron based agents, further divided into two types: reticuloendothelial system agents (e.g. Endorem) are taken up by the normal functioning liver, so that on T_2-weighted images areas of malignancy become conspicuously bright.

Hepatobiliary agents (e.g. Teslascan, Multihance, Eovist) shorten the T_1 of normal liver.

Loading

The reduction on the quality factor of the RF coil when a patient is placed inside or near to it for imaging. Often in phantom tests a loading annulus (or similar) may be used to simulate the presence of a patient.

Localiser

Images acquired initially where quality is not important but are used subsequently to prescribe diagnostic-quality images. Modern scanners acquire localiser images in all three planes. May also be referred to as scout images, plan scans or scanograms.

Logistic regression

Statistical method, where a predictive model is established from the most significant of a given number of input parameters, e.g. to classify benign and malignant disease from dynamic contrast enhanced measurements.

See also artificial neural networks.

Longitudinal plane

The plane parallel to the B_0 field (z-direction). T_1 recovery of magnetisation is in this direction and is also referred to as longitudinal relaxation.

Look-locker

Sequence used to measure T_1. Based on the inversion recovery method but utilising multiple low flip angle pulses to obtain data in a single TR.

Reference D. C. Look & D. R. Locker (1970). Time saving in the measurement of NMR and EPR relaxation times. *Rev. Sci. Instrum.*, **41**, 250–251.

Lorentz force

The force induced on a charged particle along a current carrying conductor in the presence of a magnetic field. The direction of the motion of the conductor is given by Fleming's left-hand rule (thumb = motion, first finger = field, second finger = current). In MR it manifests itself as the audible noise in the scanner produced by the vibrating gradient coils.

See acoustic noise.

Lorentzian shape

Characteristic shape (linewidth) of spectral peaks in MRS. Also used as an apodisation filter.

Low field

The design of any scanner with a magnetic field strength below 1.0 T.

See also high field.

Low gamma (γ) imaging

Phrase used to describe the utilisation of MRI for the study of MR visible nuclei with low gyromagnetic ratios relative to the proton, e.g. sodium. This is becoming possible due to the increase in field strength of many clinical scanners.

Low order phase

The small phase encoding steps, corresponding to the centre of *k*-space and responsible for the contrast/signal in the image.

See also high order phase.

Low pass filtering

Removing high frequency components from MR data, e.g. to achieve image smoothing. The filter consists of the value 1 below a certain frequency threshold and zero elsewhere. A Hanning filter may be used to reduce ringing artefacts and voxel bleeding.

See also high pass filtering.

Some medical terms you may find useful

adjuvant therapy treatment after surgery, which may include chemotherapy/radiotherapy to prevent recurrence of cancer

acidosis when blood pH falls below 7.5 (opposite is alkalosis)

albumin small blood protein

amino Acid small part of a protein molecule

anaphylaxis severe allergic reaction

aneurysm enlargement of blood vessels

antibody protein produced by cells to neutralise antigens (a substance capable of producing an immune response)

apoptosis programmed (normal) cell death

chromosome a linear strand of DNA (dioxyribonucleic acid).

diastole end of ventricle contraction

distal further away from

aetiology the causes of disease

gene a segment of DNA located in a chromosome

genome full genetic information

grey matter non-myelinated nerve tissue in the brain

hematoma pool of blood, which causes swelling

hyperplasia abnormal increase in number of cells

hypertrophy abnormal enlargement of tissue

in vitro ‘in glass’ or outside the body (e.g. test tube experiment)

in vivo in the body

necrosis cell death resulting from disease

neoplasm any new or abnormal growth referring to tumours (solid mass) or cysts (fluid).

pro-drug in-active drug when administered which breaks down to become active at some later stage
proximal close to, near
receptor molecule, which recognises specific chemical substance
sclerosis blockage in the blood vessels
systole ventricle contraction
thrombus blood clot
white matter groups of myelinated axons in the brain and spinal cord

Mm

■ 'Mag lag'

An urban myth in MR communities that frequent exposure to the scanner's magnetic field can cause memory loss or some other functional impairment.

■ Magic angle effect

Artefact that appears in parallel structures, for example in ligaments and tendons. Occurs due to the naturally short T_2 values, which become increased if these fibres are orientated at the magic angle (approximately 54°) to the direction of B_0, leading to a signal increase.

■ Magic angle spinning

In vitro technique used to acquire high resolution MRS spectra of solids. Samples are spun at the magic angle (54° to the main magnetic field), which narrows the broad MR resonance of solid material.

■ Magnet stability

See stability and also field decay.

■ Magnetic susceptibility

See susceptibility.

Magnetisation transfer

Use of off-resonance RF pulses to saturate signal from bound protons (macromolecules), thereby creating a different type of image contrast. Quantitative measurements are difficult but are beginning to be applied clinically.

Magnetisation transfer ratio

The ratio of the signal measured following the application of a magnetisation transfer (MT) pulse to the signal without the MT pulse. Ratio values are higher in white matter than in grey matter (due to myelin differences). Ratio values are reduced in demyelination.

Magnetisation vector

See net magnetisation.

Magnetogyric ratio

Alternative name for the gyromagnetic ratio.

Magnetohaemodynamic effect

The alteration in the *T*-wave of an ECG recording, due to the main magnetic field. It occurs because of the effect of the magnetic field on moving charges, and it increases with field strength.

See also ECG gating.

Magnetophosphenes

Flashing lights induced in the eyes due to rapid head motions inside or near the bore entrance of a high field scanner (4.0 T and above).

Reference J. F. Schenck, C. L. Dumoulin, R.W. Redington *et al.* (1992). Human exposure to 4.0 tesla magnetic field in a whole-body scanner. *Med. Phys.*, **19**, 1089–1098.

Magnevist

Trade name of Schering's gadolinium-based contrast agent (Gd-DTPA). The most widely used agent and one with the longest safety record.

Manganese

Common relaxation (doping) agent (Mn^{2+}). Its T_2 relaxivity is much greater than T_1 relaxivity.

Manual shim

User-controlled shimming procedure. Sometimes needed prior to imaging in exceptional circumstances, for example when the auto shim routine has failed and/or the anatomy is problematic. However, it is advisable to perform a manual shim in MRS. The user adjusts currents iteratively to the shim coils and watches the effect on the displayed water peak. See Figure 26; also see FWHM for typical values of water peak width.

See also active shimming.

MAST

Motion artefact suppression technique. A flow compensation method relying on even echo rephasing.

Matrix

The number of pixels assigned to each imaging direction. Usually the frequency is fixed to 256 or 512 but the phase is more variable (e.g. 512, 256, 128, 64). A high image matrix leads to better spatial resolution but poorer SNR.

Maximum intensity projection

Or MIP: 3D reconstruction algorithm selecting the highest pixel intensities along different paths. Used in white blood MRA to give a three-dimensional visualisation of vasculature.

See also minimum intensity projection.

Maxwell pair

Design of gradient coils consisting of a pair of opposing currents (the opposite to a Helmholtz pair). This produces a linear change in magnetic field parallel to their cylindrical axis, i.e. along the direction of B_0 in most conventional scanners (termed G_z). See Figure 11.

See also Golay coil.

MEDIC

Multi-echo data image combination. A Siemens sequence with a mixed weighting from the combination of several gradient echoes.

MEG

Magnetoencephalography. Measuring the magnetic field induced by electrical currents in the brain to elucidate brain function. Used in combination with fMRI, offering high temporal resolution but low spatial resolution.

See also *EEG*.

MEMP

Old GE term for a multi-echo multi-planar sequence. Acquisition of more than one spin echo over many slices per TR. Can be used to measure T_2 relaxation times.

See also multiple spin-echo.

Metabolite map

The integration of spectral peak areas from multiple voxel MRS data and display as a colour map, usually overlaid on to grey scale anatomical MR images. Relates metabolism to structure (see CSI). The method has been applied particularly to prostate and brain.

Reference X. Li, Y. Lu, A. Pirzkall, T. McKnight & S. J. Nelson (2002). Analysis of the spatial characteristics of metabolic abnormalities in newly diagnosed glioma patients, *J. Magn. Reson. Imag.*, **16**, 229–237.

Metallic taste

The unpleasant taste in the mouth that has been anecdotally recorded in magnetic fields of 8.0 tesla.

Microscopy

The use of very high spatial resolution to obtain high image detail. Typically referring to in-plane pixels of 100–500 μm and requiring dedicated small gradient coils.

Minimum intensity projection

Analogous to MIP but using the lowest pixel intensities. Can be used in black blood angiograms.

MIP

Maximum Intensity Projection. Written as mIP to indicate the minimum intensity projection.

Mixing time

The time between the second and third 90° pulse in the STEAM spectroscopy sequence. Controls the amount of longitudinal magnetisation that is 'stored' prior to signal detection.

MNS

Multi-nuclear spectroscopy, relating to any non-proton MRS studies.

MobiTrak

Philips moving table MR imaging technique.

Moiré fringes

Interference pattern (artefact) seen as a result of the aliasing of signals with alternating phases. A characteristic circular banding is superimposed on to the image. Most commonly observed in gradient echo images.

Molecular tumbling rate

The rate at which a molecule moves, and which governs the T_1 and T_2 of a particular tissue. Rates close to the Larmor frequency will produce a short T_1, longer and shorter rates increasing the T_1 value. T_2 is roughly proportional to tumbling rate.

See also correlation time and Bloembergen, Purcell and Pound equation.

Moment
The small magnetic field associated with spinning nuclear charges.

Moses effect
Phenomenon observed in water, which forms two peaks due to its diamagnetic properties under certain experimental conditions (requires a 8.0 Tesla field in a 5 cm bore).

See diamagnetism.

MOTSA
Multiple overlapping thin section angiograms. The use of high-resolution 3-D MRA scans which sum together to provide large coverage.

Motion artefact
See Ghosting.

Moving table
See stepping table.

MP-RAGE
Magnetisation prepared rapid acquisition by gradient echo. A 3-D version of turbo FLASH.

MR compatible
Equipment or device that is non-ferromagnetic and can therefore be used safely within the scanner (i.e. a

non-projectile). It may still cause large susceptibility artefacts, e.g. titanium needles, etc.

Reference F. G. Shellock (2001). *Pocket Guide to MR Procedures and Metallic Objects: Update*. Baltimore, PA: Lippincott, Williams & Wilkins.

MR dosimetry

The use of MR for verification of radiation doses. Involves imaging a suitable gel material with the desired radiotherapy plan, which then becomes MR visible due to radiation-induced changes in relaxation times. Usually, the material is calibrated so that absolute doses can be obtained. Earlier studies used Fricke gels (R_1 changes) but these are becoming replaced by polyacrylamide gels (R_2 changes) such as BANG and MAGIC formulations.

Reference G. P. Liney, A. Heathcote, A. Jenner, L. W. Turnbull & A. W. Beavis (2003). Absolute radiation dose verification using magnetic resonance imaging I: feasibility study, *J. Radiother. Pract.*, **3**, 120–127.

MR guided

Referring to any technique in which MR images are used to carry out a procedure. For example, a biopsy or placement of a localisation wire in the breast.

See also intervention device.

MR mammography

The increasing use of MRI for breast imaging. Contrast-enhanced MRI has very high sensitivity and specificity for

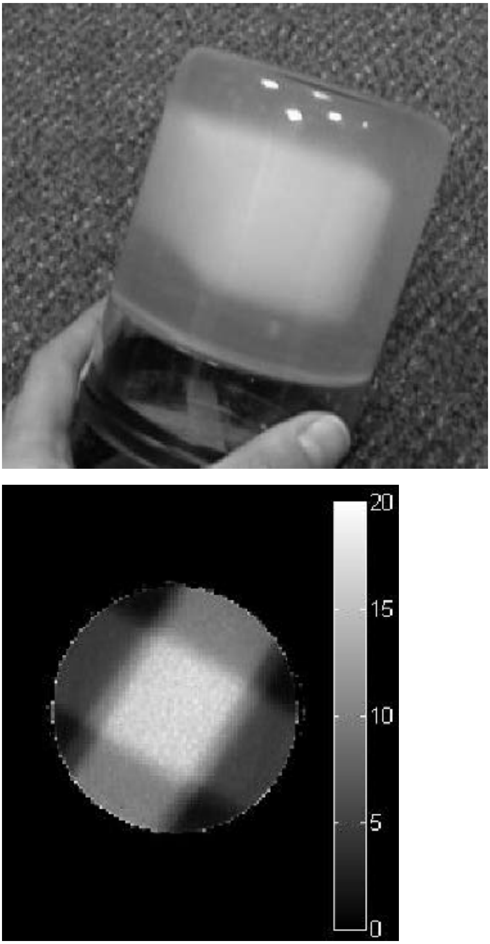


Figure 17. MR dosimetry. A polyacrylamide gel can be irradiated altering both its MR and optical properties (top). On the bottom a dose map (scale in gray) can be produced, based on radiation-induced changes in R_2 relaxation rate. (From G. P. Liney, A. W. Beavis & J. W. Goodby)

breast lesion detection. May be used in the screening of genetic cancer where young women with dense breasts (X-ray occult lesions) need to be scanned repeatedly.

Reference S. H. Heywang-Kobrunner & R. Beck (1996). *Contrast-enhanced MRI of the* Breast, Berlin: Springer-Verlag.

MR oximetry

Non-invasive measurement of blood oxygen state for example using R_2^* maps.

See also hypoxia.

MR visible

Nuclei with a non-zero spin quantum number and therefore producing an MR signal. See Appendix II for some common MR visible nuclei.

The term is also used more generally to refer to any foreign material that will show up on MR images.

MRA

MR angiography. Use of MR to image the vascular tree non-invasively. Many flow related techniques are used, such as time-of-flight and phase-contrast and increasingly contrast-enhanced MRA. Generally, techniques involve sensitising the imaging sequence to the flow of blood with resulting signal changes that are usually dependent on velocity or direction. Some techniques are able to distinguish arteries from veins.

See also peripheral MRA.

MRCP

MR cholangiopancreatography. Use of MR for non-invasive imaging of the hepatobilliary system (bile ducts, pancreas and liver).

MRS

Magnetic resonance spectroscopy. Measurement of chemical shift information rather than conventional anatomic imaging. MRSI refers to MRS imaging (see chemical shift imaging). Apart from protons, other common nuclei that are studied with MRS include phosphorus, carbon, sodium and fluorine.

MRS may be acquired either as a single-voxel or as a multi-voxel technique. Owing to the required preservation of frequency differences, localisation of the signal must be achieved without frequency encoding. Common methods include PRESS and STEAM.

MR simulator

Mock-up of a real MR scanner used to familiarise claustrophobic patients prior to their examination. More sophisticated simulators also have equipment to reproduce the noise of the scanner. May also be used to help relax patients prior to fMRI in order to achieve better results.

MR thermometry

The use of specific sequences for displaying temperature in vivo during thermotherapy (hypertherapy or cryotherapy). A probe (e.g. HIFU: high intensity focused ultrasound) is used to increase or decrease temperature in a tumour in order to achieve cell death. The progression of this temperature lesion can be detected with MR due to changes in T_1, phase, or the resonant frequency shift of water.

Reference R. Matsumoto, K. Oshio & F. A. Jolesz (1993). Monitoring of laser and freezing-induced ablation in the liver with T_1-weighted MR imaging. *J. Maga. Reson. Imag.*, **3**, 770–776.

MS-325

Blood pool agent (see angioMARK).

mT/m

The units of gradient strength. 1 mT/m is equivalent to 1 G/cm. Modern scanners have peak amplitudes of 40 mT/m.

MT

See magnetisation transfer.

MTF

The modulation transfer function. A quantitative measure of spatial resolution that is more reliable than using pixel profiles from bar patterns. A pixel profile is taken instead across an angled block to give an edge response function. The derivative of this gives the line spread function, which is fourier transformed to obtained the MTF.

See also spatial resolution.

Reference R. Lerski, J. De Wilde, D. Boyce & J. Ridgeway (1998). Quality control in magnetic resonance imaging, IPEM report no. 80.

■ MTT

Mean transit time. See transit time.

■ Multi-echo

Any sequence acquiring more than one echo collection in a given TR, e.g. multiple spin-echo or FSE.

■ Multi-planar

Referring to the multiple slice 2-D imaging capability of MRI.

See also reformat.

■ Multi-slab

Referring to the acquisition of more than one 3-D volume. For example, in time-of-flight (TOF) MRA the thickness of a volume is limited due to saturation effects and it may be advantageous to acquire multi-slabs.

■ Multi-voxel

Acquiring MRS data from many contiguous voxels (in 1-D, 2-D or 3-D) rather than a single-voxel acquisition. Has the advantage of measuring chemical information from several simultaneous regions-of-interest across an image, although the spatial resolution is limited typically to 1 cm^3.

See also chemical shift imaging.

■ Multihance

Contrast agent (from Bracco) that binds weakly and reversibly to blood protein albumin to improve the relaxivity and usefulness as a blood pool agent.

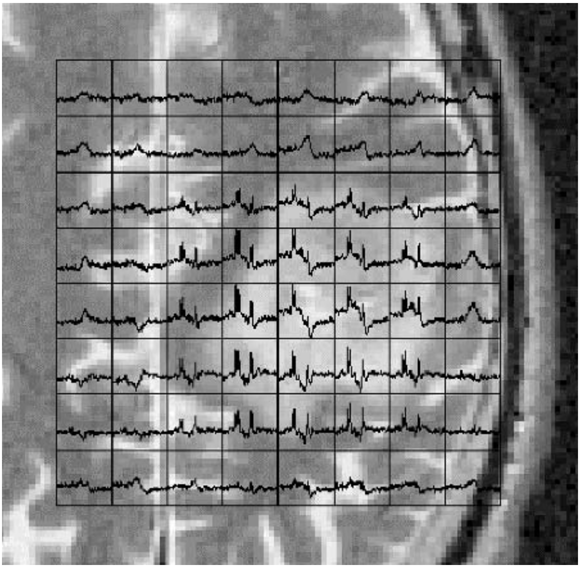


Figure 18. Example of multi-voxel MRS in the brain. A volume is pre-selected and sub-divided into contiguous voxels using phase encoding. Each grid contains a spectrum and peak areas may be displayed as a colour-scale overlay, i.e. chemical shift imaging. (Courtesy of R. Garcia-Alvarez, CMRI.)

Multiple channels

An RF coil array in which the separate coil elements have their own independent receiver components (channels). This enables signal from the coils to be combined in a useful way, for example in parallel imaging. SNR will be worse when multiple elements have only one channel.

Multiple spin echo

A spin echo sequence where more than one echo is acquired (usually four or more). Unlike the fast spin echo (FSE), the echoes are not phase encoded differently and multiple separate images are produced.

Multishot

Unlike single-shot, only part of *k*-space is acquired in a single TR, requiring more than one acquisition.

See also EPI.

M_x, M_y, M_z

Notation for the transverse (*x*,*y*) and longitudinal magnetisation (*z*) components of the net magnetisation utilised in MR.

See Appendix III.

Myocardial imaging

Cardiac MR imaging.

See also myocardial tagging and spin tagging.

Myoinositol

Metabolite occurring in normal ^{1}H MRS of the brain at 3.56 and 4.06 ppm.

Nn

NAA

N-acetyl aspartate. Metabolite seen in proton MRS of the brain, which is evident in neuronal tissue and reduced in brain tumours. Has a resonance at 2.01 and 2.6 ppm. See Figure 27 and Appendix VI.

Navigator echo

Motion correction method, which involves monitoring the signal changes in 'one-dimensional' images acquired in the direction of motion.

NbTi

Chemical formula for the niobium–titanium alloy used commonly in the main coil windings of a superconducting magnet.

Needle artefacts

Susceptibility artefacts caused by an MR compatible needle used in an MR guided biopsy. The extent and characteristic of the artefact depends on the trajectory of the needle in relation to the main magnetic field and is worse with gradient-echo sequences. Artefacts are observed along the length of the needle when the direction is perpendicular to B_0 but a blooming ball artefact is seen at the end of the needle when it is parallel to B_0. An understanding of the directional nature of these susceptibility artefacts is important in other settings, for example careful positioning in orthopaedic imaging may reduce the effects of screws, etc.

Reference J. S. Lewin, J. L. Duerk, V. R. Jain *et al.* (1996). Needle localisation in MR-guided biopsy and aspiration: effects of field strength, sequence design, and magnetic orientation. *Am. J. Radiol.*, **166**, 9.

NEMA

See DICOM.

Net magnetisation

The summation of all the individual magnetic moments. Outside of the scanner, i.e. in no external magnetic field, this value is zero. In the presence of a magnetic field, a small finite value aligned with the direction of B_0 is established and called the longitudinal magnetisation. After an excitation pulse, this component is reduced to zero and there is a full transverse component. See Figure 16.

Neutron

A particle in the nucleus of atoms, which has the same mass as a proton but zero charge.

NEX

Number of excitations. GE term for signal averaging. Note SNR $\propto \sqrt{\text{NEX}}$. May also be termed NSA, or simply averages.

Nickel

Common relaxation (doping) agent (Ni^{2+}). Its T_1 and T_2 relaxivity values are similar, and are approximately the same as copper.

See also phantoms.

NMR

Nuclear magnetic resonance, the historic term for MRI. The word 'nuclear' was dropped in the 1980s because of connotations with nuclear power. The term NMR is usually restricted to small laboratory magnets.

NOE

See nuclear Overhauser effect.

No phase wrap

Scanner option that permits imaging with a small FOV (field-of-view) without aliasing. The scanner images at a larger FOV and increases the image matrix to maintain resolution but only the desired FOV is displayed. Usually averaging is reduced to improve efficiency. Also referred to as anti-aliasing and fold-over suppression.

See also phase wrap.

Noise

The random signal contribution to the image. The main source of this signal is from thermal motion within the patient. Image noise is detected from the sensitive volume of the RF coil, which is the reason that coil sizes are constrained to the minimum required by the anatomy being imaged. The effect of noise may be reduced further by using signal averaging.

See also signal, SNR.

NSA

Philips term for number of signal averages.

See also NEX.

Nuclear Overhauser effect

The enhancement of a signal from one nuclei by actively de-coupling (saturating) the signal from an adjacent resonance. A common example of the application of this technique is in ^{13}C spectroscopy, where the carbon spectrum of a molecule is improved by interacting with a coupled ^{1}H resonance. The way the pulses are 'played out' leads to the name of Waltz decoupling.

Nucleon

An elementary atomic particle within the nucleus (e.g. a neutron or proton).

Null point

The point following an inversion (180°) pulse when the recovering magnetisation has a zero longitudinal component (M_z). The value for a particular tissue is related to its T_1 by:

$$\mathrm{TI}_{\mathrm{null}} = \ln(2) \times T_1$$

Can be utilised as a method of fat suppression, as fat, owing to a shorter relaxation time, reaches $M_z = 0$ prior to water, which maintains a small negative component. The null point for fat at 1.5 tesla is approximately 200 ms (corresponding value for water is 2 s).

See also STIR, inversion recovery and TI.

Nyquist frequency

The specific sampling at which frequency aliasing is avoided. Signal at a higher frequency than the sampling rate will be attributed an erroneously lower frequency. To avoid this, the sampling rate must be twice the highest detected frequency.

See also frequency wrap.

Nyquist ghosts

Observed at half the FOV in EPI due to timing errors. Occurs due to phase errors while scanning alternate lines of *k*-space in the opposite direction.

Oo

Oblique

Imaging in a non-orthogonal scan plane created by a combination of two of the slice-selection gradients.

See also axial, coronal, sagittal and double oblique.

OD

Optical disc. Data archiving medium, typical 2.3 GB storage. Other common media are DAT and CD.

Off-centre FOV

Imaging where the centre of the image has to be away from the isocentre, for example in shoulder imaging. This has the potential for loss of image quality.

Off-resonance

Referring to the use of a non-water centred RF pulse for example for fat or silicon selective excitation or in magnetisation transfer imaging.

Omniscan

Trade name of Nycomed–Amersham gadolinium-based contrast agent. It is a non-ionic agent chelated to DTPA-*bis*-methyl-amide, referred to as gadodiamide.

See also Gd-DTPA.

OOPS

Out of phase scanning. Deliberately creating images with fat–water out of phase artefacts (TE = 2.1 ms at 1.5 tesla). Leads to improved visualisation in certain instances, for example reduced periorbital fat in MRA.

See also DIXON method of fat suppression.

Open scanner

The design of a magnet to allow minor interventional procedures to be performed during an imaging examination. Open scanners may have either a horizontal or vertical bore design. Usually these scanners have low field strength and reduced homogeneity compared to standard tunnel configurations (typically < 5 ppm for 40 cm DSV). The majority of the scanners are of permanent or resistive types although some higher field systems are superconducting. May also be used to reduce the incidence of claustrophobia. Examples include Philips Panorama systems (0.23 T and 0.6 T), GE Profile (0.2 T) and OpenSpeed (0.7 T) and Siemens Concerto/ Rhapsody.

See also interventional device.

Optimised bandwidth

See variable BW.

Orbit X-rays

X-rays of the eyes taken prior to the MRI examination if there are any concerns about the patient history, e.g. previous metal work, shrapnel injury.

See screening.

Outer *k*-space

The edges of *k*-space that correspond to image detail.

See also high order *k*-space.

Outer volume fat suppression

Fat suppression that applies saturation bands outside the volume of interest. Useful in MRS for reducing contamination from signal outside the voxels.

See also VSS.

Overranging

Washed-out appearance of the image when the signal extends beyond the receiver range and is data is truncated. Also known as data clipping, overflow or halo artefact. It may be as a result of the dynamic range not being set properly during pre-scan, although in certain situations, e.g. during a contrast enhanced scan, the signal received may become higher than expected.

See also EDR.

Oversampling

Preventing aliasing in the frequency direction by increasing the number of measured data points (see Nyquist frequency). In most scanners frequency oversampling is always on.

See also phase and frequency wrap.

Oxygen

The naturally abundant isotope of oxygen (^{16}O) is not MR visible but the less abundant ^{17}O has $I = 5/2$. Molecular oxygen exhibits a weak paramagnetic effect and its effect (T_1 shortening) on MRI can be observed when it is dissolved in the blood. This is used in ventilation imaging when carbogen or 100% oxygen is inhaled and a comparison is made with air-ventilated images. Typically leads to 10% reduction in blood T_1 values.

Pp

Pacemakers

Devices precluded from encroaching the 5 gauss line.

See also fringe field, contraindications.

PACS

Picture archiving communication system. The drive towards digital image display and ease of storage and transfer to other hospital networks.

Palatal stimulation

Stimulation of nerves of the palate by moving the head inside a high field scanner.

See also metallic taste.

Paradoxical enhancement

Any flow-related effect resulting in bright signal rather than signal voids, e.g. in-flow enhancement.

Parallel imaging

The use of coil sensitivity profiles to replace some of the gradient encoding steps, which thereby reduces scan time. There is a trade-off in terms of reduced SNR given by:

$$\mathrm{SNR}' = \mathrm{SNR}/g\sqrt{R}$$

where g is a coil specific geometry factor (≥ 1), and R is the reduction factor (related to the number of separate coils) used. Clinical scanners use R equal to 2 or 4, although further reductions have been used in research work. Parallel imaging is being used increasingly at high field to overcome susceptibility artefacts and for high SAR sequences.

See also SENSE, ASSET and GRAPPA.

Reference J. W. Carlson & T. Minemura (1993). Imaging time reduction through multiple receiver coil data acquisition and image reconstruction. *Magn. Reson. Med.*, **29**, 681–687.

Paramagnetic

Material with a positive magnetic susceptibility, i.e. when placed in a magnetic field an internal field is induced in the direction of this field.

See also diamagnetic and ferromagnetic.

Parameter map

Processing of MR images to produce an image of some quantitative measurement on a pixel-by-pixel basis, for example, a T_2 map from separate T_2-weighted images or a permeability map from dynamic contrast enhanced data. Examples are shown in Figures **??**, 17, 19 & 31.

Partial echo

Only part of the echo is sampled thereby reducing scan time. Equivalent to acquiring only the right-hand side of k-space. Also called asymmetric, fractional or half echo.

Partial flip

Use of a less than 90° flip angle for excitation. In certain situations (TR $\ll T_1$) the signal is optimised by using a small flip angle. It arises from the mathematical rule that, for small angles $\cos\alpha$ 1, i.e. the transverse component of magnetisation is $M_0 \sin\alpha$ while the longitudinal component is practically unchanged ($M_0 \cos\alpha$ M_0).

See Ernst angle and gradient-echo.

Partial fourier

Reduced imaging time by acquiring a fraction of the phase encoding steps. Partial fourier usually refers to acquiring the bottom half of *k*-space rather than partial k-space, which is less specific. In practice slightly more than half of the lines of *k*-space are acquired. Also called halfscan, half fourier, partial NEX and ½ NEX. Three-quarters of *k*-space may be acquired in so-called ¾ NEX imaging.

Partial *k*-space

Imaging technique where only part of *k*-space data is acquired in order to speed up imaging time. Conventionally, lines of *k*-space are filled left-to-right by frequency encoding and bottom-to-top by incremental phase encoding per TR. In partial echo only the right half of *k*-space is acquired. In partial fourier, only the bottom half of *k*-space is collected. Partial *k*-space refers to any general reduction of *k*-space data collection. Missing data may be filled in from the conjugate symmetry properties of *k*-space.

See also key-hole imaging.

Partial saturation

Operating with a TR sufficiently short that full T_1 relaxation is not achieved.

See also steady state.

Partial volume

The reduction of image signal and contrast when spatial resolution is large compared to the structure(s) being studied, so that adjacent structures of different signal intensity appear as an average signal in the same image voxel.

Parts per million

See PPM.

Passive shielding

Shielding making use of steel placed at certain parts of the magnet. Now obsolete and replaced by active shielding.

See also fringe field.

Passive shimming

The use of ferromagnetic plates positioned inside the windings to improve the homogeneity of the main magnetic field.

See shim and active shimming.

'Patient right'

Referring to the conventional radiological presentation of images such that the patient's right side is displayed on the left of axial and coronal images (see Figure 2).

Patient table

Part of the scanner on which the patient is positioned and landmarked. The table then moves into the magnet isocentre. The table may be detachable for ease of transfer of some ambulant patients.

PC

Phase contrast. MRA technique where the amount of phase change caused by a gradient is determined by flow along the gradient direction.

See also velocity encoding, even echo re-phasing.

PD

See proton-density.

Peak area

The integrated area under a peak in the MR spectrum, which is proportional to the number of spins at that resonant frequency. The peaks are usually obtained by fitting the spectrum to a suitable model (the linear combination or LC model is often used: this compares the data to a set of standard reference peaks).

See also PNR.

Peak area ratios

Method of quantifying metabolite concentrations in MRS by determining the peak area relative to some other peak. The denominator may be a non-varying peak or a peak expected to show opposite changes to the numerator in order to improve the sensitivity of the measurement.

See also absolute peak quantification.

PEAR

Philips sequence, abbreviation of phase encoded artefact reduction. Utilises real-time adjustment of *k*-space filling, which is dependent on the position of the diaphragm. A method for respiratory gating.

Perfusion

Blood flow at the capillary level, or more specifically the flow rate per unit of tissue mass. Used in both cancer imaging and also stroke, where diffusion may over-estimate the ischemic area.

Perfusion imaging

Various techniques for imaging and monitoring tissue perfusion. Can be subdivided into arterial spin labelling and dynamic susceptibility contrast methods. The second method uses a contrast agent and T_2^* images to examine tissue perfusion via susceptibility effects as the agent traverses through capillaries. Signal is seen to decrease in the perfused region, and blood volume and flow can be mathematically described. Usually an arterial input function is also required.

See also cerebral blood volume.

Reference F. Calamante, D. L. Thomas, G. S. Pell *et al.* (1999). Measuring cerebral blood flow using magnetic resonance imaging techniques. *J. Cereb. Blood Flow Metab.*, **19**, 701–735.

Peripheral MRA

MRA technique usually performed with contrast enhancement to image the vessels of the arms/legs. Lower peripheral MRA requires moving table scans, plus dedicated RF coils and/or double doses of contrast to improve signal.

Peripheral nerve stimulation (PNS)

Harmless but unpleasant effect experienced in the fingers/nose induced by rapid gradient switching. PNS typically occurs around 60 T/s but is dependent on gradient rise times. The threshold for nerve stimulation in humans has been modelled* and a useful expression, which fits experimental data is given by:

$$\frac{\mathrm{d}B}{\mathrm{d}t} = 54\left(1 + \left(\frac{132}{t}\right)\right)$$

where t is the rise time in μs.

Potentially fatal cardiac stimulation occurs well above this threshold (for rise times <1 ms). Zoom gradients reduce this effect even at high switching rates by reducing the extent of the gradient. Alternatives to gradient encoding, e.g. parallel imaging, are also used to further speed up imaging time without this problem.

See also db/dt.

Reference *J. P. Reilly (1992). Principles of nerve and heart excitation by time-varying magnetic fields. *Ann. NY Acad. Sci.*, **649**, 96–117.

Peripheral pulse gating

Particular gating method using a light transducer (photoplethysmograph) attached to the fingertip to detect pulse rate. Changes in blood volume in the nail bed alter the light reflected back to the photodetector. More reliable at high field than ECG gating.

See also PQRST wave.

Peristaltic motion

Semi-random patient motion of the intestine. May cause motion artefacts in abdominal imaging. Can be reduced by administering an anti-peristaltic agent, e.g. buscopan or fasting for 4 hours prior to the scan.

Permanent magnet

MR scanner constructed from ferromagnetic material in which a field has been established during manufacture. They tend to be very heavy but have low running costs and achieve fields of about 0.2–0.3 T. Early types used iron–cobalt alloys but modern versions use rare alloys such as samarium–cobalt and neodymium–iron–boron, which reduces the weight. Most clinical scanners today are of the superconducting type, although many open scanners use permanent or resistive magnets.

PET

Positron emission tomography. It is a specific nuclear medicine technique utilising high energy positron emitting nuclides, which are detected using coincidence detectors. Often used in functional studies and can be compared to fMRI, but with disadvantages of poorer spatial resolution and ionising radiation.

PGSE

Pulsed gradient spin echo.

pH measurement

MR measurement of cellular pH, which may be important in cancer studies. In MRS the chemical shift of phosphorus metabolites can determine pH. Novel Gd-based contrast agents that are pH sensitive are also being developed.

See also inorganic phosphate.

Phantom

Any material or test object that is designed to mimic the patient when imaged. Simple designs consist of water-filled spheres doped to reduce relaxation times to those seen in vivo (see doping). At high fields, water may be replaced by oil to reduce standing wave artefacts. More complicated designs may be composed of multiple compartments or glass objects for quality assurance tests.

Reference E. L. Madsen & G. D. Fullerton (1982). Prospective tissue-mimicking materials for use in NMR imaging phantoms. *Magn. Reson. Imag.*, **1**, 135–141.

Pharmacokinetic modelling

Computationally intensive method of applying a real physiological model to contrast enhancement data to determine tissue-specific parameters or descriptors. Common descriptors include K^{TRANS}, K_{ep} and V_e.

Reference P. S. Tofts (1997). Modelling tracer kinetics in dynamic Gd-DTPA MR imaging. *J. Magn. Reson. Imag.*, **7**, 91–101.

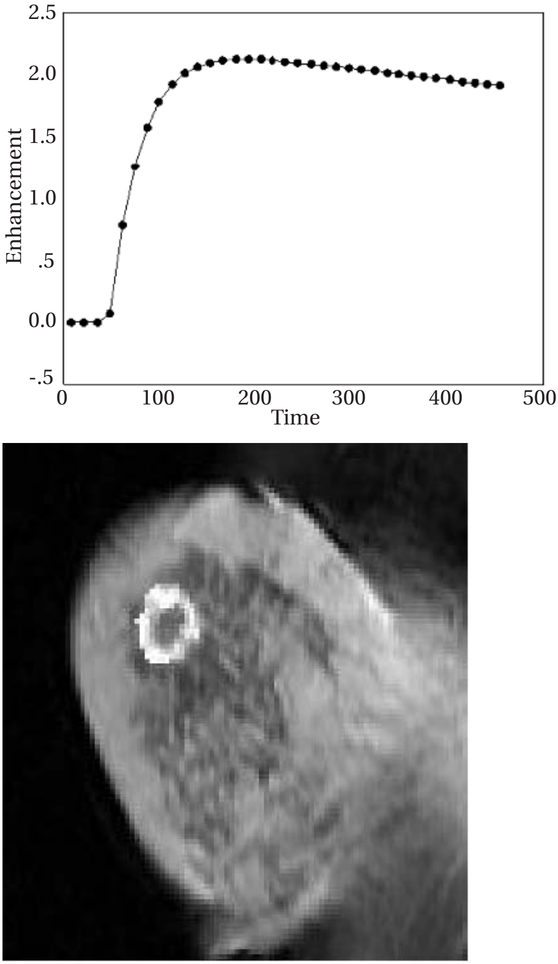


Figure 19. Pharmacokinetic modelling of breast lesion uptake during a chemotherapy trial. The enhancement (shown above), is fitted on a pixel-by-pixel basis to produce a parameter map of K^{TRANS} (below), with high values seen around the rim of the tumour. (Courtesy of M. Pickles, CMRI.)

Phase

The description of the position on the 'clock face' attributed to spins as they precess in the transverse plane. Initially, all the spins tipped into the transverse plane by the excitation pulse are said to be in phase. Subsequently, the frequencies of each spin change so that they have different positions or phases relative to each other (see dephasing).
Note: Number of phases is also used to refer to the number of times a single slice is imaged in a dynamic scan.

Phase correction

Manual or automated method of adjusting the phase of MRS data so that the peaks in the spectrum all appear above the baseline. Phase correction may be zero order (involving a linear offset of phase) or first (or higher) order requiring a more complicated transformation.

Phase encoding

The use of incremental changes in gradient amplitude in order to spatially discriminate signal along a particular direction by changes of phase. Unlike frequency encoding it must be repeated hundreds of times. The number of increments of the phase-encoding gradient, and therefore the scan time, is determined by the image matrix in the phase encoding direction. This typically varies from 64 to 512. Certain artefacts are demonstrated uniquely in this direction, e.g. phase wrap while other artefacts are more dominant in this direction, e.g. ghosting and ringing. Ringing is usually seen in the phase direction as this is often the smaller matrix dimension due to time constraints.

Phase sensitive demodulator

Hardware component, which acts as a double balanced mixer in reverse: it removes the RF component from the detected signal. This signal is then sent to the analogue-to-digital converter to be processed by the computer.

Phase (I,II,III . . .) trials

Different stages of testing associated with a new drug (e.g. one of the numerous novel MRI contrast agents) involving initial animal tests, small clinical trials and so on, prior to release on the commercial market.

Phase wrap

See aliasing. *Note:* phase wrap also occurs in the through-plane direction in *3-D* imaging.

Phased array

See array.

Phosphocreatine

The main spectral peak in phosphorus MRS, and used as the reference (i.e. set to 0 ppm). See Figure 20.

Phosphodiesters

Spectral peak seen in phosphorus MRS at 3.0 ppm.

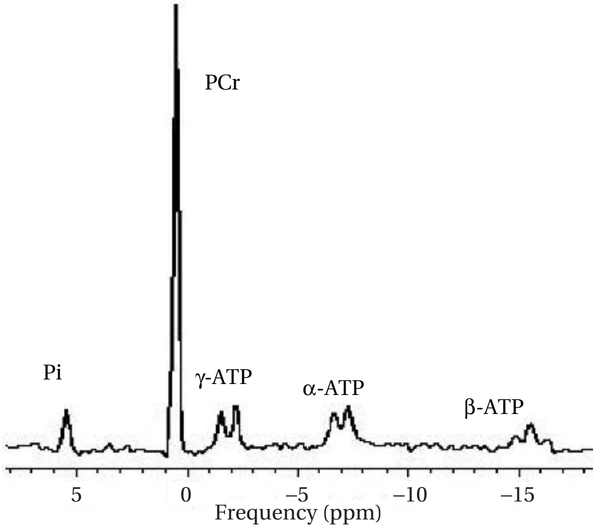


Figure 20. Phosphorus MRS example. Spectrum from healthy muscle in a study of metabolism. Note the wide dispersion and excellent SNR compared to proton in Figure 27. Peaks are Pi: inorganic phosphate, PCr: phosphocreatine and the three peaks from adenosinetriphosphate. (Courtesy of P. C. Tan, CMRI.)

Phosphorus

MR visible isotope (^{31}P), used in MRS for examining metabolism. It has a resonant frequency at 1.5 tesla of 25.9 MHz, and a chemical shift range of 30 ppm, which means the spectral peaks are more easily distinguished than with proton MRS. Also used in cancer studies (e.g. hepatic tumours).

See also dual tune.

Photoplethysmograph

A device for monitoring the patient's pulse from either their fingers or toes in peripheral pulse gating.

Pianissimo

Toshiba scanner with the first vacuum lined bore design to reduce acoustic noise. Similar designs are now common in most high field clinical systems.

Pixel

A single image (picture) element defined by the field-of-view divided by the image matrix. The pixel refers more to the 2-D display on the monitor/computer; however, it should be remembered that the signal comes from a three-dimensional cuboid (and is therefore more correctly termed a voxel).

Pixel intensity is the brightness of each element and in a parameter map it indicates the value of the parameter itself.

PNR

Abbreviation of peak-to-noise ratio. It is the spectroscopy equivalent value to the measure of SNR used in imaging, and is taken as either the peak amplitude or the peak area divided by a representative signal taken in the baseline of the spectrum.

PNS

See peripheral nerve stimulation.

Point spread function

Determines how signal from one point is spread over the reconstructed image. Concerned in MRS with signal contamination from outside voxels.

POMP

Phase offset multi-planar. This is a method of speeding up imaging time by acquiring two slices at once using a composite RF pulse. Cannot be used where anatomy extends beyond the FOV in the phase direction.

Posterior

Referring to the rear side of patient anatomy. It is the bottom of an axial image and the right of a sagittal image (see Figure 2).

See also anterior.

Ppm

Parts per million. The common reference scale used to report metabolite peaks in MRS. Each nucleus has a standard reference peak, which is set to 0 ppm. Other peaks are then quoted as a frequency difference from this:

$$\text{ppm} = 10^6 \times (\nu - \nu_{\text{REF}})/\nu_{\text{REF}}$$

where ν, and ν_{REF} are the frequencies of the metabolite and the reference peak. For ^{1}H and ^{13}C the reference is TMS (tetramethylsilane). In ^{31}P it is phosphocreatine. The advantage of using the ppm scale is that it is independent of field strength.

See also chemical shift.

PQRST wave

Characteristic ECG (electrocardiograph) wave pattern. *P* is associated with atrial contraction, QRS ventricular contraction and *T* ventricular rest. Cardiac gated images are triggered from the *R*–*R* interval. In peripheral gating the peak signal appears approximately 250 ms after the actual ECG *R* wave.

Preamp

Part of the receiver system, which moderately amplifies the inherently weak MR signal with a minimal addition of noise.

See also ADC and phase sensitive demodulators.

Pre-emphasis

A method of counteracting eddy current effects by using distorted current waveforms for the gradient coils so that, when combined with eddy currents, the desired linear field is produced.

Pregnancy

Currently, it is advised that pregnant women should not be scanned within their first trimester, although there is no proof of any harmful effects to the fetus.

See contraindication.

Prescan

Automatic or manual routine performed by the scanner or operator prior to each imaging scan. It involves shimming the prescribed volume, tuning the centre frequency and setting the receiver and transmitter amplifiers appropriately by playing out the sequence with zero phase encoding to produce the maximum signal amplitude. In MRS additional operations, e.g. water suppression, may also be performed.

PRESS

Point resolved spin echo. Type of spectroscopy localisation sequence based on a spin echo. It uses a 90°–180°–180° pulse sequence in the presence of slice selection gradients in each orthogonal direction to excite a small voxel. Inherently produces better SNR than STEAM, although minimum echo times are longer. PRESS also exhibits chemical-shift related misregistration, which can be improved by using larger bandwidths in techniques such as PROSE.

Reference P. A. Bottomley (1987). Spatial localisation in NMR spectroscopy in vivo, *Ann. NY Acad. Sci.*, **508**, 333–348.

PRESTO

Principals of echo shifting with a train of observations. Utilised by Philips as a whole-head fMRI/perfusion sequence using a steady-state-based EPI acquisition. Prone to motion artefacts.

Reference G. Liu, G. Sobering, J. Duyn & C. T. W. Moonen (1993). A functional MRI technique combining principles of echo-shifting with a train of observations (PRESTO). *Magn. Reson. Med.*, **30**, 764–768.

PROBE

GE single or multiple voxel MRS sequences. Abbreviation for proton brain examination.

See also PROSE.

Profile phantom

Test object consisting of angled glass or Perspex plates and used for measuring the nominal slice profile. Pixel values taken along the plates reveal an inverted signal peak, which is related to the slice profile b by:

$$b = \text{FWHM} \times \tan\alpha$$

where FWHM is the full width at half maximum height of the inverted peak (given in units of distance) and α is the angle of the plate.

Usually, measurements are taken from plates of opposite angulation and a geometric mean is taken to account for slight misalignment of the phantom ($<5^\circ$).

ProHance

Gadolinium-based contrast agent, similar to Gd-DOTA, with one CO group replaced by $CH(OH)(CH_3)$, resulting in a non-ionic complex.

Projectile

Effect of a ferromagnetic object brought close to the scanner. Strong fields are induced within the object, which propels it into the scanner bore. The force of attraction is proportional to the mass of the object and inversely proportional to the

square of its distance from the field.
Objects deemed safe at 1.5 T may not be safe at 3.0 T.

Projection reconstruction

The original method of MR image reconstruction from a series of projections acquired at many angles.

See also filtered back projection and fourier transform.

Prone position

Imaging with the patient lying on their front, for example in a conventional breast MR examination.

See also supine.

PROPELLER (periodically rotated overlapping parallel lines with enhanced reconstruction)

A partial *k*-space sequence from GE where *k*-space is traversed radially at different angles ('blades') to reduce the effects of non-periodic motion and susceptibility artefacts.

See also *k*-space trajectory.

PROSE

GE spectroscopy sequence designed specifically for use in the prostate (abbreviation of prostate spectroscopy examination). It utilises spectral-spatial RF pulses in order to reduce mis-registration and improve lipid suppression. The shape and narrow bandwidth of the excitation pulse is such that the lipid peak at 1.3 ppm is not excited ($< 1\%$), while only 5% of the water peak is excited for referencing chemical shift.

PROSET

Philips utilisation of a binomial pulse for fat suppression.

Proton

Referring to the spin or nucleus of the common isotope of the hydrogen atom, which consists of a single proton.

See also deuterium.

Proton decoupling

Sequence designed to actively decouple proton resonances to improve the discrimination of other nuclei.

See also nuclear Overhauser effect.

Proton density

Image contrast where the T_1 and T_2 weighting is minimised so that the contrast of the image is determined by the number of proton spins (amount of water). Requires a short TE and long TR.

Proton density or PD (unlike T_1 and T_2) is not measured routinely. Proton-density weighted images may be used for native tissue T_1 correction in contrast enhanced data. They also demonstrate the white and grey matter differences in the brain. At long TR (12 s), CSF appears bright (100% PD), followed by grey matter (78%) and white matter (70%).

PD may differ from true water content due to short T_2 components, which are not seen in MRI.

Reference S. Gutteridge, C. Ramanathan & R. Bowtell (2002). Mapping the absolute value of M0 using dipolar field effects, *Magn. Reson. Med.*, **47**, 871–879.

Proximity limits

Some critical objects, and the maximum fringe field they can tolerate, in gauss, are given below:

Inside 30 G: stainless steel, non-ferromagnetic objects
Outside 30 G: ECG monitors, unrestrained ferromagnetic objects
Outside 10 G: credit cards, floppy discs, X-ray tubes
Outside 5 G: pacemakers, public access, etc.
Outside 3 G: moving cars, etc.
Outside 1 G: TVs, monitors (CRT), CT and PET scanners
Outside 0.5 G: railways, gamma cameras.

Reference P. McAtamney & D. Shaw, *Siting and installation*, in *Practical NMR Imaging*, ed. M. A. Foster & J. M. Hutchison, IRL Press, Oxford.

Pseudolayering

The appearance of contrast agents in the bladder. Towards the base of the bladder, where concentrations are high, the T_2 shortening effect predominates, resulting in a low signal intensity, whereas a bright signal band is observed superior to this layer, due to T_1 relaxation.

Reference A. D. Elster, W. T. Sobel & W. H. Hinson (1990). Pseudolayering of Gd-DTPA in the urinary bladder. *Radiology*, **174**, 379.

PSIF

Steady-state sequence with the pulse diagram being the reverse of the FISP sequence. It has a prominent T_2 weighting.

Pulse

See RF pulse.

Pulse controller

Hardware component that manages the timing of the spectrometer and gradients during the imaging sequence.

Pulse programming

Creation and manipulation of non-standard pulse sequences by the operator in order to implement user-specific imaging.

Pulse sequence

A set of RF and gradient pulses of fixed duration and separation, which are used to produce an MR image. The sequence is represented in a pulse sequence diagram (Figure 21). The gradients are shown as rectangles, with the area representing the amplitude and duration drawn either above or below the baseline to indicate a positive or negative sense.

Pulsed gradient spin echo

Or PGSE sequence. Alternative name used to describe the Stejskal–Tanner diffusion weighted acquisition.

See also DWI.

P-value

The probability that there is no difference between two data sets. Usually a low *P*-value threshold is used (e.g. $P < 0.05$ is

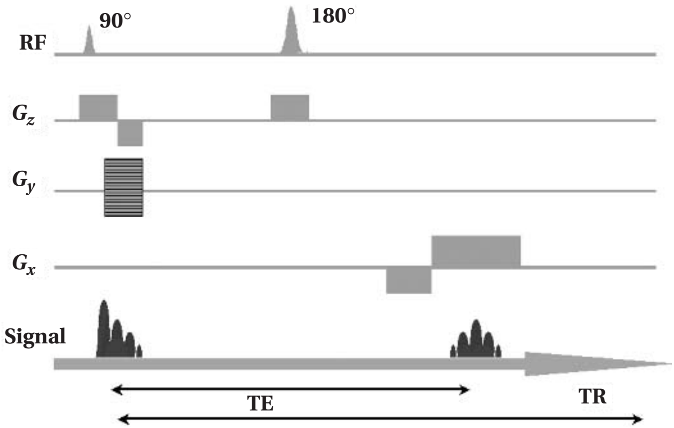


Figure 21. The basic (axial) spin-echo pulse sequence. A 90° excitation pulse is applied in the presence of a slice-select gradient (*z*-direction) to produce a FID. At TE/2 a 180° refocusing pulse recovers T_2 signal at time TE. At this point, frequency encoding discriminates the signal along *x*-direction. Phase encoding (*y*-direction) is carried out by incremental steps over many repetitions. Note the use of dephasing lobes along G_z and G_x.

equivalent to a 5% probability that differences have occurred by chance).

See also t-test, bonferroni correction and statistical errors.

Reference B. S. Everitt (2003). *Medical Statistics from A to Z*, Cambridge: Cambridge University Press.

Qq

Quadrature

The use of two receiver coils set 90° apart to detect the signal unambiguously. Measuring the signal twice represents an improvement in SNR of $\sqrt{2}$ compared to non-quadrature (linearly polarised) coils. The detected signal may be reconstructed from either channel (called real and imaginary) but, more usually, the magnitude of both components is used. The phase of the signal may also be reconstructed. Errors involved in the quadrature detection lead to ghosting. Quadrature coils are also more efficient at transmitting RF power and therefore produce less *SAR* in the patient.

See also RF coils.

Quality factor

The quality or Q factor refers to the tuning of the RF coil and is defined by the amplitude and width of the resonant peak (tall and narrow meaning a high Q). RF coils are designed to work well for a range of Q factors since patient loading will alter this characteristic.

Quality assurance (QA)

Acceptance testing of a recently installed scanner or a more routine quality control check. Usually, a daily QA is performed by imaging a manufacturer-specific phantom to establish scan quality visually. A more thorough and less frequent set of tests may be performed using specifically designed phantoms, which may include:

(i) a homogeneous or floodfill phantom, used for measuring SNR, uniformity and ghosting
(ii) a phantom comprising an arrangement of plates for testing slice profile and spatial resolution
(iii) a phantom with a grid of known dimensions for estimating geometric distortion
(iv) various test objects of different relaxation times to determine sequence contrast and relaxation time accuracy.

Usually, tests are performed with the head and body coils using a standard spin-echo sequence. A more comprehensive QA programme may include additional RF coils. Advanced sequences such as EPI, may be examined for ghosting and stability. Safety tests may include the validation of the fringe field and a measurement of acoustic noise using specialist equipment. Some systems offer a semi-automated QA tool requiring minimal operator intervention. See floodfill, slice profile, resolution, contrast and gel phantoms.

See also SNR, uniformity, geometric distortion, ghosting and linearity.

Reference R. Lerski, J. De Wilde, D. Boyce & J. Ridgeway (1998). Quality control in magnetic resonance imaging. *IPEM Report No. 80.*

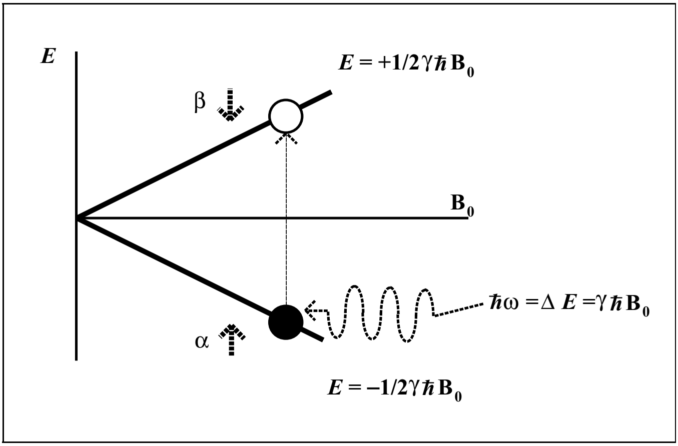


Figure 22. Energy level diagram for a proton in a magnetic field. Its quantum number is equal to ½, resulting in two spin states. The energy difference between the spin up (α) and spin down (β) state increases with magnetic field strength. Application of the RF pulse at the resonant frequency causes a transition between states.

Quadrupole–electric interactions

The mechanism that dominates relaxation in nuclei with spin quantum numbers greater or equal to 1 (e.g. ^{23}Na). Interactions are with the electric field of another nucleus rather than with the magnetic field.

Quantum number

The discrete number (*I*) assigned to nuclei, according to their spin properties. Can be whole or half integers for nuclei with an odd number of protons or neutrons. Most commonly studied nuclei have $I = {}^1\!/_2$, examples are ^{1}H, ^{31}P, ^{13}C and ^{19}F. Nuclei with I greater than 1 exhibit quadrupole–electric interactions. Nuclei with an even number of protons and neutrons have $I = 0$, and the nuclei are said to be not MR visible. Examples include ^{16}O and ^{12}C. See Appendix II.

The quantum number also governs the possible number of energy states (or Zeeman levels) in an external magnetic field, equal to $2I + 1$. For the proton ($I = 1/2$), and there are two such states defined as spin up and down.

Quench

The process that occurs after a superconducting magnet loses its superconductivity and the cryogens begin to boil violently and escape from the cryostat. The onset of a quench is indicated by a loud noise, tilting of the image and, unless the gases are properly vented, a white vapour emerging into the scan room, which causes an increase in pressure and a drop in temperature. A quench may be described by the colour of the vapour (normally ‘white’ or ‘black’, which indicates the permanent loss of the magnet).

See also cryogens, superconducting magnet, boil-off.

Rr

R_1

Longitudinal relaxation rate ($=1/T_1$) with units of s^{-1}.

R_2

Transverse relaxation rate ($=1/T_2$) with units of s^{-1} has been shown to correlate with hepatic iron content in patients with iron-overload.

R_2^*

Transverse relaxation rate ($=1/T_2^*$) with units of s^{-1} used in cancer studies to probe tumour hypoxia.

Radiotherapy planning

The use of high anatomic detail provided by MRI for radiotherapy planning. Conventional CT images, used for electron density calculations, are registered with MRI. In certain situations where the anatomy is homogeneous, e.g. in the brain, an overall assumed electron density can be used and only MR is needed for planning. See Figure 5.

Reference A. W. Beavis, P. Gibbs, R. A. Dealey & V. J. Whitton (1998). Radiotherapy treatment planning of brain tumours using MR images alone. *Br. J. Radiol.*, **71**, 544–548.

RACE

Real-time acquisition and velocity evaluation. A 1-D technique where a very rapid sequence is used to image across a blood vessel and measure the velocity of blood.

Radian

Alternative unit for describing flip angles. 2π radians are equal to 360° (a 90° pulse is also referred to $\pi/2$). Note that angular frequency ω is measured in radians per second and is given by $2\pi f$ where f is the frequency in hertz.

Ramp up/down

The process by which the magnetic (B_0) field is turned on or off in a scanner. In a superconducting scanner an external power supply is applied and then a superconducting switch is used to short-circuit the magnet once the desired field is established. Ramp time may also be used in association with gradients although rise time is more accurate.

Ramp sampling

Measuring or sampling the MR data while the gradient is yet to achieve its maximum amplitude, i.e. during the rise time of the gradient. This improves efficiency of the image acquisition.

Ramped RF pulses

Use of variable flip angles in time-of-flight sequence (see TOF and TONE). The flip angle is increased along the slice direction to combat the saturation of the flowing signal.

RARE

Rapid acquisition with relaxation enhancement. Generic name for sequences such as FSE and TSE.

Raw data

MRI or MRS data prior to any post-processing. Specifically, it refers to time domain data before fourier transformation.

Readout gradient

Synonym for the frequency encoding gradient.

Real

Signal from one of the receiver channels in quadrature detection. Usually denoted I (in phase). The non-imaginary part of a complex number.

See also imaginary.

Real time fMRI

fMRI acquisition, where images are acquired and processed 'on the fly' so that the stimulus paradigm may be stopped when sufficient activation has been detected (e.g. brainwave by GE).

Receiver

RF coil and associated hardware used to detect the MR signal. During pre-scan, the receiver and transmitter are adjusted to accommodate the range of signal. On GE systems the R_1 and R_2 values are used to report the receiver gains. Similarly, there are two FFT scales for Siemens scanners.

Reconstruction

The process of fourier transformation and display of the image or spectrum following data acquisition. Modern scanners perform this with near simultaneity so that there is no appreciable delay. Reconstruction speeds are quoted in seconds per 256×256 image and may be 0.01 s or better.

Errors in reconstruction lead to characteristic herringbone artefacts.

Rectangular FOV

Reduction of the image matrix in the phase encoding direction in order to obtain a non-square imaging area or field of view. Useful for avoiding phase wrap or imaging rectangular-shaped anatomy at shorter scan times. May be denoted as RFOV and a percentage value indicating the fraction of the reduction.

Reduced flip angle

Using smaller than normal flip angles (e.g. 90° or 180°) in sequences with long echo trains in an attempt to reduce the SAR given to the patient. For example, 150° may be used instead of 180° in a fast spin-echo sequence.

Refocusing pulse

The application of an RF pulse at time t, to recover the phase of spins and produce a spin-echo at time $2t$. The optimum refocusing occurs when the flip angle is 180° (or π). See Figure 28.

Reformat

Displaying image data in another image plane from the one in which it was acquired, e.g. the data is acquired axially, but reformatted in the coronal plane. Best results are obtained with thin contiguous slices or true 3-D imaging.

Registration

Term relating to matching two image data sets in space, for example MRI and CT images for radiotherapy planning, or different dynamic images to correct for movement. Also referred to as image fusion.

Region-of-interest

See ROI.

Relaxation

Referring to the mechanisms that affect excited spins once the RF energy has been removed, leading to a return to the equilibrium position where the net magnetisation is aligned with the main magnetic field.

See T_1, T_2 and T_2^*.

Relaxivity

The property of a contrast (relaxation) agent that determines its ability to shorten relaxation times. Changes in relaxation time are given by:

$$R_1' = R_1 + k_1 \times D$$

$$R_2' = R_2 + k_2 \times D$$

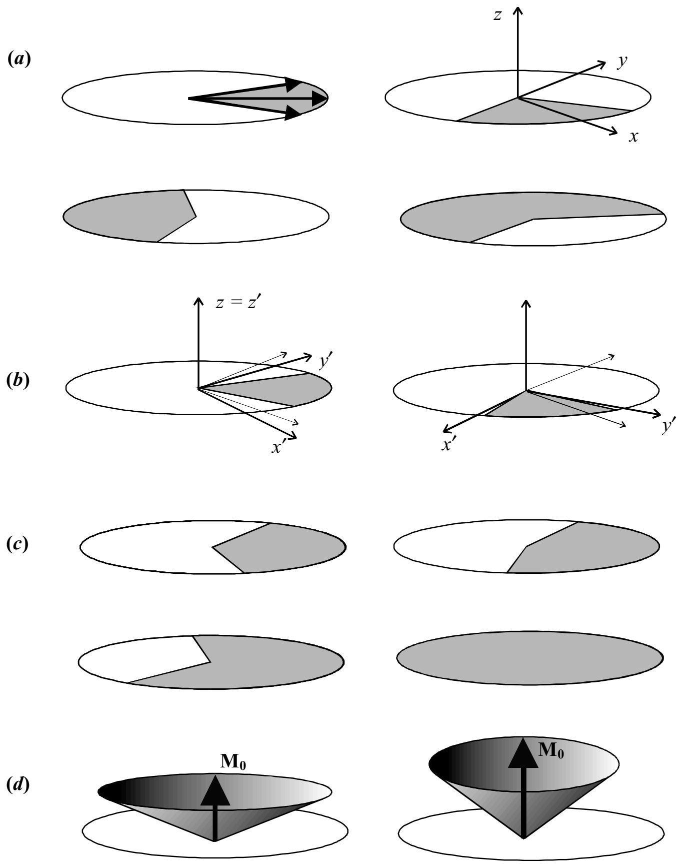


Figure 23. Relaxation. (*a*) In the laboratory frame of reference, the *x*–*y* axis is fixed and the spins dephase due to T_2^* decay but are also seen to rotate around B_0. (*b*) By adopting the rotating frame of reference the dephasing is simplified as shown in (*c*). T_1 recovery is a much longer process and effectively begins after complete T_2^* decay. The net magnetisation M_0 recovers along the *z* (*z*′) axis as shown in (*d*).

where D is the concentration of the contrast agent, R_1 (or R_2) is the native tissue relaxation rate, R_1' (R_2') is the new rate and k_1 (k_2) is the contrast agent relaxivity.

The values of k_1 and k_2 for Gd-DTPA at 1.5 tesla are 4.5 and 5.5 $mM^{-1}\ s^{-1}$.

Other agents that can be used to dope water in the construction of phantoms include copper and agarose gel.

Repetition time

See TR.

Residual water

The remaining water peak observed in ^1H MRS following water suppression. Typically, this may be reduced by a factor of several hundred. The signal from residual water may be used to set the chemical shift of other metabolites.

Resistive magnet

Type of scanner utilising an electromagnet, which can be turned on or off, and requiring large amounts of electrical power and usually water cooling. This type has a lower field strength than the superconducting type. It can be air cored or iron cored, providing fields of up to 0.2 T and 0.6 T, respectively. Resistive windings can be used to augment the field produced by permanent magnets in hybrid designs, reducing the power and weight of the separate types.

Resolution phantom

Test object comprising a series of glass plates with varying separations (bar patterns). The nominal resolution can be checked visibly against the appropriate bars or the modulation of pixel profiles taken across the plates can be evaluated.

See also MTF.

Resonant frequency

See Larmor frequency.

Respiratory compensation (gating)

Synchronising the sequence to the periodicity of respiration. Uses pressure bellows to monitor patient breathing and gate the images accordingly to reduce the effects of this motion.

See also ROPE.

REST

Regional saturation. Philips use of saturation bands outside of the imaging volume to reduce flow and motion artefacts.

Restricted diffusion

Diffusion, which is limited by cell boundaries. May be investigated using DWI if the diffusion times t_d, are sufficiently long. In free diffusion the mean displacement is proportional to the diffusion time. However, if there is restriction, the measured diffusion will reach a plateau at increasing values of t_d.

Reference D. Le Bihan (1995). Molecular diffusion, tissue microdynamics and microstructure. *NMR Biomed.*, **8**, 375–386.

Rewinding gradients

Use of gradients to re-phase spins at the end of a sequence, for example in FSE and FISP type sequences.

Reynolds number

Dimensionless quantity that predicts the onset of turbulent flow (see flow phenomena). It is defined as the product of fluid density, vessel diameter and velocity divided by viscosity. Generally, laminar flow is present for Reynolds numbers less than 2100.

RF

The radio-frequency component of the electromagnetic spectrum, i.e. in the frequency range of 0 to 3000 GHz, which includes radar, UHF, television and microwave. At 1.5 tesla the proton frequency is 63.8 MHz RF.

RF antenna

Synonym for RF coil.

RF artefact

See Zipper artefact.

RF burns

Patient burn induced by poor positioning of the RF coil (e.g. crossed cables) and a high SAR scan. The most common adverse reaction in MRI, but virtually unknown below 1.0 tesla.

RF coil

Small coil surrounding the patient or specifically the anatomy of interest tuned to the Larmor frequency and producing the B_1 magnetic field. The coils can be receive or transmit only or a combined transceiver. Common types of RF coil include surface coil, solenoid coil, birdcage coil and saddle coil.

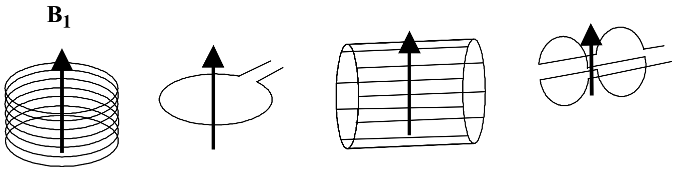


Figure 24. RF coils. The four general designs are (left to right), multiple turn solenoid, single turn surface coil, birdcage coil and saddle coil. All produce the B_1 field in the direction shown, and all but the solenoid are used readily in horizontal bore scanners.

The resonant frequency ω of the coil is related to both its inductance L and its capacitance C by:

$$\omega = 1/\sqrt{LC}$$

The RF coil should be of similar size to the anatomy of interest in order to maintain good SNR, as the signal comes from the imaged slice but the noise is from the entire sensitive volume of the coil.

RF effects

The heating in tissue due to application of RF pulses. See SAR. May be of particular concern in patients with thermoregulatory problems and in the testis or fetus, for example.

RF penetration

See skin depth.

RF power

The amount of RF energy needed (and therefore deposited to the patient) during the imaging sequence. The RF power P is given by:

$$P = 2\omega_0 B_1^2 V_c / \mu_0 Q$$

Where V_c is the coil volume. Q is the quality factor of the coil, which drops with increasing frequency so that P is proportional ω_0^2. This necessitates the use of increased RF power at high field.

See also SAR.

RF pulse

Transient application of a resonant magnetic field perpendicular to B_0 (referred to as B_1) for the purposes of perturbing the net magnetisation. Usually employed as an excitation or a refocusing pulse. The pulses are described as being selective (soft pulse), i.e. in the presence of a gradient field they influence only a finite section of spins, or non-selective (hard pulse), which affect the entire sensitive volume of the RF coil. The pulse controller unit ensures the accurate timing and amplitude of the RF pulses.

RF shielding

Also called RF screening. The copper-lined wall of the scan room to stop RF interference causing RF artefacts. The cables and connections to the RF coils also need to be shielded carefully.

See Figure 25 and Faraday cage.

RF shimming

Optimisation of the RF field prior to imaging, which is essential at very high field (> 3.0 tesla), where poor RF penetration becomes problematic.

Rho

Greek symbol (ρ) used to indicate proton-density.

Rim enhancement

Characteristic appearance of the well-perfused periphery of a tumour, which preferentially enhances during a contrast-enhanced scan, while the necrotic core takes up little contrast.

Ringing

Artefacts seen at high-contrast interfaces (see Gibbs). Also known as a truncation artefact.

Rise time

The finite time taken to achieve the maximum amplitude of the gradient. Typical rise times are several hundred μs.

See also fall time.

ROC curve

Receiver operating characteristic curve. A plot of the sensitivity of a particular technique against 1-specificity. Often used to chose between diagnostic methods, e.g. MRI and ultrasound.

RODEO

Rotating delivery of excitation off resonance. Gradient echo sequence using RF pulses centred on either fat or water to suppress signal from one or the other. Known as PROSET on Philips.

ROI

Region-of-interest. User-defined subset or area of an image from which the pixel intensities may be recorded or subsequently processed.

Reference G. P. Liney, P. Gibbs, C. Hayes, M. O. Leach & L. W. Turnbull (1999). Dynamic contrast-enhanced MRI in the differentiation of breast tumours: user defined versus semi-automated region-of-interest. *J. Magn. Reson. Imag.*, **10**, 945–949.

ROPE

Respiratory ordered phase encoding. Method of respiratory motion compensation using pressure bellows to monitor respiratory motion and re-ordering the *k*-space acquisition so that consecutive lines of data are acquired at similar points of the cycle.

Rotating frame

Frame of reference in which the observer is also rotating at the Larmor frequency so that the spin appears stationary, as opposed to the laboratory frame of reference. Simplifies the action of RF pulses. See Figure 16.

RR interval

The time between consecutive parts of the ECG waveform used in the timing of gated sequences. Typically, the resting heart rate may be 75 bpm with an RR interval of 800 ms, which may be reduced to 400 ms during stress or exercise.

Ss

Saddle

RF coil design, which produces a B_1 field perpendicular to the long-axis direction. See Figure 24.

See also birdcage coil.

Sagittal

Image plane acquisition, which divides the patient into right and left, i.e. the slice selection is in the *x*-direction and the in-plane directions are head to foot (top to bottom) and anterior–posterior.

See also coronal, axial, oblique. See Figure 2.

Saline flush

Volume of saline (0.9% NaCl) administered to the patient intravenously to ensure complete delivery of an MR contrast agent.

SAR

Specific absorption rate. It is the amount of RF power deposited as heat to the patient and is expressed in W/kg. This figure increases quadratically with field strength, necessitating the use of lower flip angle sequences or parallel imaging techniques at 3.0 tesla and above. Currently NRPB guidelines limit whole-body SARs to 1–4 W/kg. SAR is related to flip angle α, and duty cycle D as follows:

$$\text{SAR} \propto B_o^2\, \alpha^2 D$$

Studies have been performed to monitor the temperature rise in animals and also volunteers for given MR sequences. The Adair* model demonstrates that a core temperature rise of only 1°CC occurs during 1 hour exposure to 4 W/kg, although this is dependent on ambient temperature.

Reference *E. R. Adair & L. G. Berglund (1986). On the thermoregulatory consequences of NMR imaging. *Magn. Reson. Imag.*, **4**, 321–333.

Saturation bands

Using slice selection in combination with dephasing gradients to remove signal, which may otherwise cause unwanted effects, e.g. in flow compensation or outside MRS voxels.

Saturation recovery

Using a 90° pulse and repeating the experiment for several different TRs in order to measure T_1.

See also inversion recovery.

Saturated spins

The state of constant magnetisation (partial saturation) achieved at the end of the pulse sequence when $\text{TR} < T_1$.

Unsaturated spins have their full equilibrium magnetisation available at the end of the repetition time, i.e. they are fully relaxed ($\text{TR} \gg T_1$) or they are 'fresh' and have not been subject to prior RF excitation.

Scalar coupling

See J-coupling and AX, AB systems.

Scanning, 4-D

Term often used to describe the acquisition of multiple (or dynamic) 3-D volumes with the fourth dimension referring to time, e.g. in contrast-enhanced *MRA*.

See also time-resolved MRA.

Scan percentage

Used by Philips scanners to indicate the reduction in *k*-space acquisition.

See partial *k*-space.

Scan room

Specially constructed room to site the MR scanner (Figure 25).

See also Faraday cage and control room.

Scan time

See acquisition time.

SCIC

GE term meaning surface coil intensity correction. Processing method to improve the homogeneity of surface coil images.

See also coil uniformity correction.

Scout images

See localiser images.

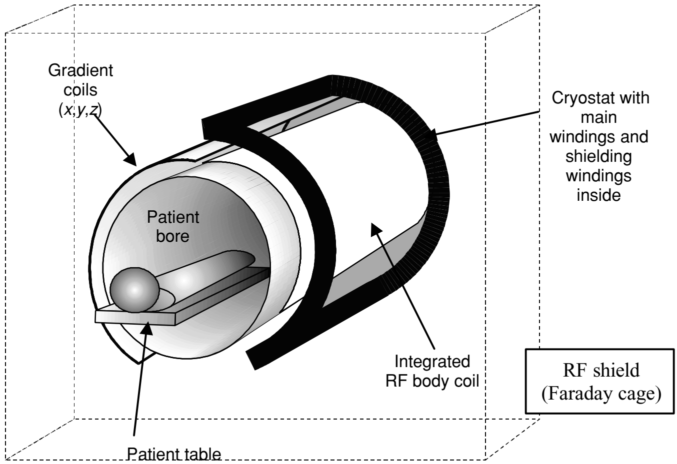


Figure 25. Cut-away diagram showing various parts and their relationship inside the scanner. Separate gradient coils are required for each orthogonal direction. In addition, there will be windings for the shim coils and gradient shielding (not shown).

Screening

Performing appropriate checks of the patient to ensure there are no contraindications for MRI. Typical examples of this may include credit cards, keys, make-up and surgical devices. May require orbit X-ray prior to examination.

Screening constant

Alternative name for the shielding constant.

Seed point

User-defined pixel that forms basis of further image processing, e.g. region growing, thresholding, etc.

Segmentation

Removal or isolation of connecting pixels which are within a given signal intensity threshold. Permits the volume of structures to be readily measured or visualised.

Segmented *k*-space

Cardiac imaging technique that permits multiple stages (frames) of the cardiac cycle to be imaged during a breath-hold. Within each RR interval, a small portion (or segment) of k-space is filled for each frame in the cardiac cycle. For example, if this is set to 32 segments for a 128 matrix, then 32 *R–R* intervals (heartbeats) are required, each acquiring 4 lines of *k*-space (referred to as four views per segment). The number of possible frames is dependent on heart rate, segments and TR.

SENSE

Sensitivity encoding. Parallel imaging method, similar to SMASH except it operates in the imaging domain. Images with fewer phase encoding steps are unwrapped using a knowledge of coil sensitivity profiles. Commercially implemented by Philips.

Reference K. P. Pruessman, M. Weiger, M. Scheidegger & P. Boesiger (1999). SENSE: sensitivity encoding for fast MRI. *Magn. Reson. Med.*, **42**, 952–962.

Sensitive volume

The region from which the RF coil may detect signal or more crucially noise, meaning it is prudent to select an appropriately sized coil to optimise SNR.

Sequential

Dynamic scanning where all images corresponding to one slice location are acquired before the next slice. The opposite of an interleaved acquisition.

Sequential *k*-space filling

The conventional order in which image data is collected and *k*-space is filled, i.e. starting with the most negative phase encoding and incrementing in a positive sense. See Figure 15.

See also centric *k*-space.

Shielding

The action of reducing the extent or effects of a magnetic field. Shielding is used for the main magnetic field or gradient fields and can be described as either active or passive shielding. May also refer to RF shielding.

Shielding constant

Dimensionless quantity characterising the effect of the electron cloud of an atom to reduce the magnetic field experienced by the nucleus. The value increases with the number of electrons and varies from 10^{-6} to 10^{-2}.

See chemical shift.

Shim

The action ('shimming') of improving the homogeneity of the main magnetic field by adding small corrective fields. This is achieved by either passive shimming or active shimming.

Global shimming refers to the whole sensitive volume of the coil, whereas local shimming applies to a small volume of interest. See also manual and auto shim. In MRS the homogeneity (quality of the shim) is crucial for good resolution of spectral peaks.

Shine through

When the desirable weighting effect is dominated by another, e.g. at high b values, the diffusion decay may appear artificially bright due to areas with a long T_2 value ('T_2 shine through').

Shinnar-le-roux

Special-shaped RF pulse with a sharp slice profile, which is superior to conventional sinc pulses.

Short bore

MR scanner utilising modern technology to reduce the bore length. Particularly used in conjunction with 3.0 tesla scanners, which can now be made with comparable lengths to that of a 1.5 T machine. The front-to-back dimension of a short-bore 3.0 T scanner is 1.7 m.

Signal

Coherent contribution to the final image.

See also SNR and noise.

Signa

GE scanner model (1.5 T and 3.0 T).

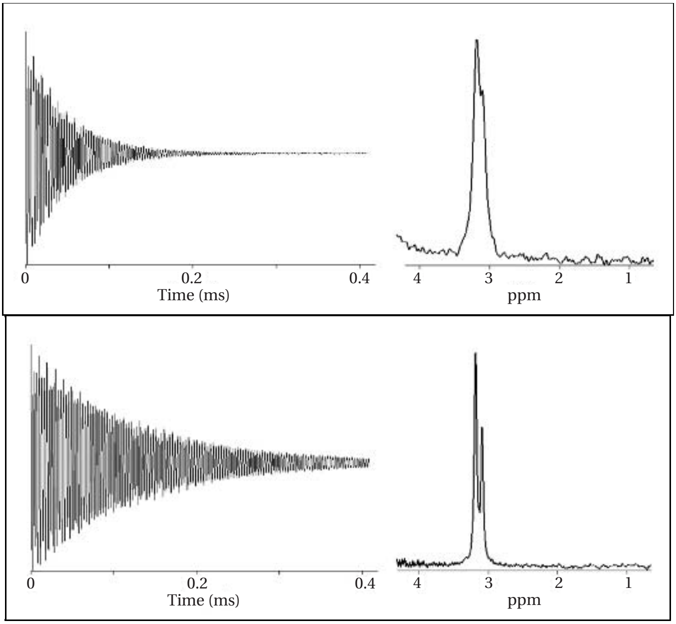


Figure 26. Guide to **Shimming**. In MRS the quality of the 'shim' (or how homogeneous the B_0 field is) directly influences the appearance of spectral peaks. The FID (time domain) on the left is fourier transformed to give the choline and creatine peaks on the right (frequency domain). Adjusting the shim coils causes the FID to be extended, resulting in resolution of the two closely spaced peaks (*bottom*).

Silicon

Proton resonance detectable in many breast implants. Its resonant frequency is 100 Hz from fat (320 Hz from water) at 1.5 tesla.

Silicon specific

Suppression of water and fat peaks in order to image the silicone resonance in breast implant patients for investigation of rupturing, etc.

Sinc shaped

A mathematical function described as:

$$\sin x/x$$

It is the fourier transform of a square wave, i.e. the time domain signal of an ideal slice profile.

Single dose

Amount of contrast agent dose administered per unit of body weight. Gd-DTPA is licensed up to triple doses of 0.3 mmol/kg.

Single shot

EPI sequence in which the entire *k*-space data is collected in one repetition time (TR). Typically, a slice can be imaged every 50 ms.

See also EPI factor and multishot.

Single voxel

MRS technique in which slice selection is performed in each orthogonal direction to localise the signal from the common intersection or voxel.

See also CSI.

Skin depth

The effect of finite RF penetration in a conducting body, e.g. patient. This becomes worse at high field (>3 tesla) and

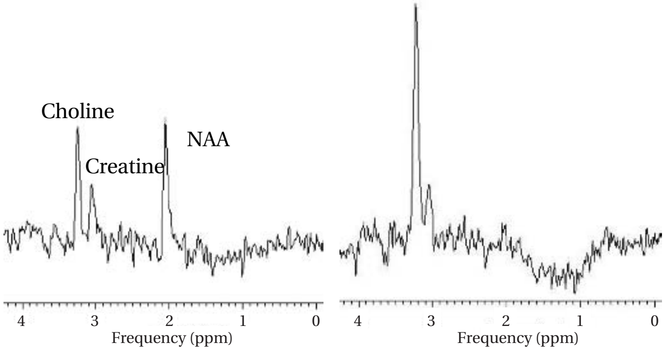


Figure 27. Example of a **single voxel** ^1H MRS study: (*left*) normal brain tissue demonstrates an NAA peak. (*right*) In a malignant tumour the NAA peak is absent and there is an elevation of choline.

necessitates the use of increased RF power, which in turn accentuates the SAR problem. The RF skin depth is defined as:

$$\sqrt{2/\mu_0\mu_r\sigma\omega}$$

where μ_0 is the permittivity of free space, μ_r the relative permittivity of the sample, σ, conductivity, and ω, is the RF frequency. Skin depth also affects the quality factor of the RF coil.

See also B_1 doming.

Slab

The finite volume which is phase encoded in 3-D imaging. Sometimes this is divided into partitions.

See multi-slab.

Slew rate

Gradient specification taking into account both the rise time and maximum amplitude. Given as:

$$\text{slew rate} = \text{amplitude}/\text{rise time}$$

Typical slew rates range from 20 to 150 mT m^{-1} ms^{-1}.

Slice

The finite section of imaged volume in 2-D imaging.

Slice gap

The space between consecutive slices. Usually set to 10% of the slice thickness to account for cross-excitation. This may be increased to 20% in the case of STIR. May also be called spacing or slice interval.

Slice profile

The shape of the excited cross-section. Ideally, this should be rectangular, requiring an infinitely long sinc pulse in the time domain. In practice, the pulse is truncated leading to a more rounded profile and causing cross-excitation.

Slice selection

The application of a finite bandwidth RF pulse in the presence of a linear gradient to excite a section of spins in a direction perpendicular to the gradient. The gradient has an initial dephasing lobe (negative sign) to ensure that only frequency of the spins are changed. See Figure 21.

Slice warp

The deviation of the imaging slice from a true perpendicular orientation to the slice selection gradient. It is investigated using an appropriate test object, which consists of a series of rods, running parallel to the slice direction. Deviations from the actual rod separations reveal the degree of warping.

See also quality assurance.

SMASH

The simultaneous acquisition of spatial harmonics. A parallel imaging method for speeding up imaging time by replacing some phase-encoding steps with linear combinations of receiver coils. Similar to SENSE but involves combining time domain signals with a knowledge of sensitivity profiles, prior to reconstruction, i.e. it operates in *k*-space rather than in imaging space like SENSE.

Reference D. K. Sodickson & W. J. Manning (1997). Simultaneous acquisition of spatial harmonics (SMASH): fast imaging with radiofrequency coil arrays. *Magn. Reson. Med.*, **38**, 591–603.

SNR

Signal-to-noise ratio, the ratio of signal from the imaging slice to the random noise picked up from within the entire sensitive volume of the receiver coil. Can be improved by using small anatomy-specific RF coils, large voxels and signal averaging. It becomes worse with increasing receiver bandwidth.

SNR is measured in a floodfill phantom. There are many different methods for defining SNR, the two main methods are:

(i) subtraction method: two separate but otherwise identical images are acquired. SNR is taken to be equal to the mean signal in one image divided by the SD in the subtracted images.

(ii) conventional method: mean signal from a ROI in an image is divided by the SD of signal from a region in the background avoiding ghosts.

There are no ideal values for SNR and it is difficult to compare across systems unless coil quality and filling factors are accounted for. It remains a useful routine QA measure for monitoring system performance but is not very specific. It is also sometimes written as *S/N*. See also NEX and CNR.

Reference R. Lerski, J. De Wilde, D. Boyce & J. Ridgeway (1998). Quality control in magnetic resonance imaging. IPEM Report No. 80.

Sodium

^{23}Na MR visible isotope, with four energy states ($I = 3/2$). Sodium imaging is being used increasingly in the heart for studies of infarction.

See also quantum number.

Reference T. Pabst, J. Sandstede, M. Beer, W. Kenn, S. Neubauer & D. Hahn (2003). Sodium T_2^* relaxation times in human heart muscle. *J. Magn. Reson. Imag.*, **15**, 215–218.

Soft tissue

The unique contrast capability of MRI permitting the imaging of internal organs, etc. Unlike CT which demonstrates bony anatomy well but has low soft-tissue contrast.

Solenoid

Very efficient RF coil design used to produce a magnetic field along the long axis of the coil. As such, it is not particular useful in conventional horizontal bore scanners. May be a single or multiple turn design. See Figure 24.

SPAIR

Philips sequence similar to SPIR fat suppression but very insensitive to B_1 inhomogeneity.

SPAMM

Spatial modulation of magnetisation. Name given to spin tagging in cardiac imaging.

Spatial domain

The fourier transform of time domain data.

Spatial resolution

The nominal pixel size of the image determined (in-plane) by the FOV divided by imaging matrix. Through-plane resolution is determined by slice thickness (for 2-D imaging) or the slab thickness divided by the second phase encoding matrix for 3-D imaging. The spatial resolution may be measured in a suitable phantom, comprising a bar pattern of plates with varying separations and widths. A visual inspection of a pixel profile taken across these plates indicates whether the appropriate resolution has been achieved. A threshold of 50% modulation (the relative peaks and troughs) is acceptable. Both phase and frequency should be tested, by swapping encoding directions and changing the phantom orientation.

Usually the resolution is poorer in the phase encoding direction. An alternative method utilises the edge of a block to determine the modulation transfer function (see MTF).

Reference R. Lerski, J. De Wilde, D. Boyce & J. Ridgeway (1998). Quality control in magnetic resonance imaging. *IPEM Report No.* 80.

Specific absorption rate

See SAR

Spectral editing

Referring to a variety of methods that take advantage of relaxation time or coupling differences in order to facilitate the identification of spectral peaks.

Spectral resolution

Referring specifically to the frequency range (spectral or sweep width) of the MRS data divided by the number of time domain points measured. Typically, a ^{1}H spectrum may be acquired with a 2500 Hz spectral width and 1024 time domain points.

Spectroscopy

See MRS.

Spectrometer

Part of the scanner, which is able to generate and detect discrete frequencies.

See also pulse controller.

Spin

Fundamental property of a charged atomic particle. It is quantised (i.e. can only take discrete values) and characterised by the spin quantum number.

Spin angular momentum

The momentum of an atomic particle due to spinning on its axis (an electron also possesses orbital angular momentum).

Spin echo

The basic MR pulse sequence using a 90° excitation RF pulse followed by a 180° refocusing pulse in order to recover T_2^* decay and produce an echo signal which has decayed due to T_2 alone.

Signal in a spin-echo sequence is given by:

$$S \propto [1 - \exp(-\mathrm{TR}/T_1)]\exp(-\mathrm{TE}/T_2)$$

(The pulse sequence diagram for a spin echo is shown in Figure 21.) Other types of echo are gradient echo and stimulated echo.

Spin-lattice relaxation

Synonym for T_1 relaxation.

Spin–spin relaxation

Synonym for T_2 relaxation.

Spin quantum number

See quantum number.

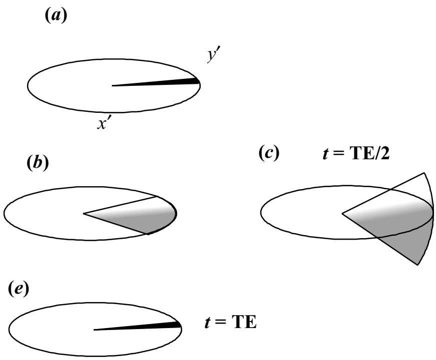


Figure 28. Spin-echo. (*a*) Spins tipped into transverse plane after the initial 90° pulse. (*b*) Spins dephase due to T_2^* effects so that the faster spins (grey) are ahead of the slower spins (white). (*c*) At time TE/2, a 180° refocusing pulse is applied. (*d*) The result is that the phase order of the spins has been reversed so that the faster spins are now behind the slower spins. (*e*) At time TE, the spins have rephased to produce a spin echo, which has decayed due to T_2.

Spin states

The possible number of energy levels a spin has when placed in a magnetic field. Equal to $2I + 1$ where I is the spin quantum number. The energy difference between these spin states increases linearly with magnetic field. For the proton, the spin states are referred to as spin up and spin down. See Figure 22.

Spin tagging

Also known as myocardial tagging or SPAMM. Cardiac imaging method whereby rows and columns of spins are saturated deliberately in order to produce dark grid lines on the image, which can be used to visually monitor cardiac wall motion and thickness. A 1-D equivalent method is also used. The darkness of the tags fades during the cardiac cycle due to T_1 recovery.

Spin up (down)

Possible spin states of nuclei with $I = {}^1\!/_2$ (for example, a proton) when placed in a magnetic field: spin-up (sometimes labelled α), where the spins are aligned with B_0 and the higher energy spin-down state (β) corresponding to anti-parallel alignment. At thermal equilibrium there is a slight majority of spins in the lower energy state causing a net magnetisation. Application of RF energy induces a transition between these states. See also Figure 22.

Spinor

The peculiar quantum physics property of the spin wave function where a 360° pulse is not equivalent to 0° but a 720° pulse is!

SPIO

Super paramagnetic iron oxide. Specific type of contrast agent.

See also USPIO.

SPIR

Spectral saturation with inversion recovery. Method of fat suppression combining both chemical selective (CHESS) and STIR methods, implemented on Philips scanners.

See also SPAIR.

Spiral EPI

Type of EPI sequence where the gradients are played out in such a way as to traverse *k*-space in a spiral direction. See Figure 15.

See also constant and blipped EPI and k-space trajectory.

Spoiling

The active destruction of transverse magnetisation by applying appropriate gradients or RF pulses at the end of the sequence. Used in rapid gradient echo techniques such as FSPGR.

SS

Used as a prefix in sequences to indicate that these are single shot.

SSRF

Spectral-spatial RF pulses (GE), which do not excite fat and thereby improve quality of MRS data.

See also PROSE.

Stability

Important quality assurance measure for fMRI indicating how consistent the signal baseline is. Ideally, the percentage signal variation should change by no more than 0.5% over several minutes. Often, a warming-up period may need to be observed before the scanner performs in a stable fashion. Also refers to the stability of the magnetic field (see field decay).

STAIR

Solution and tissue attenuation inversion recovery. Pulse sequence that uses two 180° inversion pulses with two different inversion times. Can be used in a similar way to a combined STIR and FLAIR sequence with TIs equal to 180 ms and 2 s in order to suppress fat and CSF in the brain and enable an improved visualisation of grey matter.

Reference T. W. Redpath & F. W. Smith (1994). Use of a double inversion recovery pulse sequence to image selectively grey or white matter. *Br. J. Radiol.*, **67**, 1258–1263.

Standing-wave artefact

Increased signal in the centre of the image observed at higher field strengths due to the dielectric effect.

See also B_1 doming.

Static field limits

Below are the NRPB recommended safety limits for workers exposed to static magnetic fields.

$$8\text{ h mean} = 200\text{ mT}$$

$$\text{maximum} = 2\text{ T (whole body) and } 4\text{ T (extremities)}$$

Reference National Radiological Protection Board (UK) (1993). Board statement on restrictions on human exposure to static and time varying electromagnetic fields and radiation. *Doc. Natl Radiat. Prot. Board.*, **4**, 5.

Station

Referring to the patient table position during a moving table acquisition. For example, in whole body screening or peripheral

MRA the imaging may be performed at three or more stations.

Statistical errors

A type I error arises from using an inappropriately large *P*-value to assign significance to data, which results in a positive test by chance. In statistical terms this equates to the null hypothesis being rejected falsely.

An over-small *P*-value results in a type II error (the null hypothesis is accepted falsely), where real significance in data is not detected. See bonferroni correction.

Type A errors can be classified as errors associated with repeat measurements and type B errors include all other errors.

Reference B. S. Everitt (2003). *Medical Statistics From A to Z*, Cambridge: Cambridge University Press.

Steady state

The situation after several repetitions of RF pulses, where the magnetisation recovers to a constant level and is said to be in a steady state.

See also saturation.

Steady-state sequence

Sequences that maintain a transverse magnetisation by using a TR shorter than T_2. True steady-state sequences are sometimes called 'coherent' whereas spoiled techniques that dephase the transverse magnetisation actively can be called 'incoherent'.

See also FISP and GRASS.

Steal effect

Vascular supply that is taken from elsewhere, due, for example, to arterio-venous malformation (AVM), and leading to possible functional impairment. Also observed in tumours with poor vessel integrity.

STEAM

Stimulated echo acquisition mode. Type of spectroscopy localisation sequence using three 90° RF pulses and slice selection in each orthogonal direction to excite the intersected volume or voxel. Produces a stimulated echo and therefore less signal than PRESS but has better voxel definition.

Reference J. Frahm, H. Bruhn, M. L. Gyngell, K. D. Merboldt, W. Hanicke & R. Sauter (1989). Localised high-resolution proton NMR spectroscopy using stimulated echoes: initial application to human brain in vivo. *Magn. Reson. Med.*, **9**, 79–93.

Stejskal–Tanner

Commonly used bipolar gradient arrangement in DWI. Generally referred to as the pulsed gradient spin-echo scheme. Two gradients of opposite polarity are applied, stationary tissue is equally dephased and rephased, whereas moving spins accrue a net phase loss and appear as a signal loss. By using large amplitude gradients, the sequence is sensitised to diffusional motion.

See also b-value.

Reference E. O. Stejskal & J. E. Tanner (1965). Spin diffusion measurements: spin-echoes in the presence of a time-dependent field gradient. *J. Chem. Phys.*, **42**, 288–292.

Stepping table

MRA technique where the patient is moved and imaged at different stations to obtain full peripheral coverage. Also known as moving table and MobiTrak (Philips).

Stereotactic

Referring to any device for localisation in 3-D space. For example, prior to surgical removal of brain tumours, imaging with an MR visible stereotactic frame attached to the skull is performed to localise the tumour accurately.

Stimulated echo

Type of echo produced from three or more RF pulses. The transverse magnetisation created by the first pulse is 'stored' in the longitudinal plane by the second pulse, and recalled by the third pulse. Used in the STEAM MRS sequence. In total, five echoes are produced (one stimulated and four spin echoes).

The signal of the stimulated echo is given by:

$$S \propto \frac{M_0}{2} \sin\,\alpha_1 \sin\,\alpha_2 \sin\,\alpha_3\;\exp(-2t_a/T_2)\exp(-t_b/T_1)$$

where t_a and t_b are the times between the first and second RF pulses and $\alpha_1 \ldots \alpha_3$ are the flip angles of each pulse. For maximum amplitude, three 90° pulses are used (e.g. STEAM).

STIR

short TI inversion recovery (or short tau inversion recovery, referring to the symbol used for inter-pulse times, τ). Inversion recovery sequence using a short TI (inversion time) of about 180 ms at 1.5 tesla to suppress fat. The signal is acquired as fat reaches the null point but water still has a non-zero magnetisation.

See also fat suppression.

Stray field

See fringe field.

Stress-perfusion agent

Pharmaceutical administered to induce stress on the heart for the study of myocardial perfusion (see cardiac MR). Agents include vasodilators (e.g. adenosine) and others, which enhance the contractility of the heart (dobutamine).

Stroke

Damage to the brain caused by the interruption of blood supply.

See also ischemia and diffusion.

Superconducting magnet

Scanner using an air-cored electromagnet with windings constructed from material with zero electrical resistance below a certain temperature (approaching absolute zero, $-273\ ^\circ$C). Typically, a niobium–titanium (Nb–Ti) alloy set in a copper core is used. Comprises 90% of MRI scanners in use.

See also permanent and resistive magnets.

Superior

Referring to the direction of the patient's head. The opposite of inferior. It is the top of a sagittal and coronal image (see Figure 2).

Supine position

Imaging position with the patient lying on his/her back as opposed to prone imaging.

Surface coils

Simple RF coil consisting of a loop of wire and used as receive-only. The B_1 profile of the coil is poor, with excellent SNR proximal to the coil plane, which quickly drops off further away.

The magnetic field at a distance d from a coil of radius a is given by the Biot–Savart law and is:

$$B = ka^2/(a^2 + d^2)^{3/2}$$

Good SNR is obtained at distances equal to the radius of the coil. Single coils can be combined to form arrays.

Surface rendering

3-D visualisation technique where the outer or border pixels of a structure are segmented and displayed as a surface. Reduces the amount of displayed data and can speed up rotation of the image, etc.

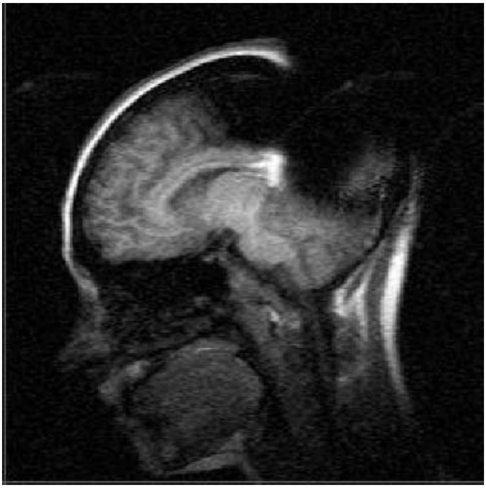


Figure 29. Huge susceptibility artefact caused by a volunteer who managed to be imaged with a hair clip in place.

Surgical planning

The use of advanced MRI techniques (especially fMRI) to highlight sensitive functioning brain tissue so that this may be spared during surgery.

Reference W. Golder (2002). Functional magnetic resonance imaging – basics and applications in oncology. *Onkologie*, **25**(1), 28–31.

Survey scan

Another term for the initial localiser scan.

Susceptibility

Property of matter that determines how easily it becomes magnetised when placed in an external field. Interactions between the field and the orbiting electrons within the material can either augment (paramagnetic and ferromagnetic) or disperse (diamagnetic) the external field.

Susceptibility artefact

Characteristic signal voids and distortions present in the image, due to differences in susceptibility between foreign objects and tissue or between certain tissues themselves, e.g. air-tissue interfaces. This artefact becomes worse at high field. The phase loss due to this artefact is given by:

$$\Delta\phi = \gamma G_i \Delta r \mathrm{TE}$$

where G_i is the local gradient caused by the susceptibility difference, Δr is the voxel size and TE the echo time.

Sweep width

See spectral resolution.

Symphony

Siemens scanner model.

Tt

Tailored RF pulse

The change in shape of an RF pulse so that its magnitude varies with time to create a suitable slice-selective pulse.

See slice selection, sinc-shaped.

Talairach space

Standard co-ordinate system used in the analysis of fMRI to enable different studies to be compared. The origin of this system is set to the anterior commissure (the AC–PC line) and *x*,*y*,*z* co-ordinates are used to refer to the left–right, anterior–posterior and superior–inferior distances from this position.

t-test

Statistical test used in medical research to compare the differences in the mean values of two groups of data. An appropriate level of significance (see *P*-value) must be used.

Also see Bonferroni correction.

T_1

Longitudinal or spin-lattice relaxation time. Related to the recovery of the net magnetisation (M_0) back to its re-alignment with B_0.

The magnetisation in the longitudinal plane (*z*-axis) is given by:

$$M_z = M_0(1 - \exp(-t/T_1))$$

T_1 is the time taken for the net magnetisation in the z-direction (M_z) to recover to 63% ($1 - e^{-1}$) of the equilibrium value (M_0). See Figure 23 and Appendix IV for some examples.

Note: T_1 increases with field strength as $B_0^{1/3}$. It can be measured using inversion or saturation recovery or Look–Locker sequences.

See also BPP equation.

T_1-weighted

A sequence where signal contrast in the image is determined predominantly by differences in T_1 relaxation times. A short TE to minimise T_2-weighting and a short TR is used (e.g. TR 250–700 ms and TE 10–25 ms).

T_2

Transverse or spin–spin relaxation time. Related to the dephasing of the net magnetisation following the removal of the excitation pulse B_1.

This decay of magnetisation in the transverse plane (x–y axis) is given by:

$$M_{xy} = M_0 \exp(-t/T_2^*)$$

Here $T_2{}^*$ is the time taken for the magnetisation to decay to 37% (e^{-1}) of its initial value. See Figure 23 and Appendix IV.

Note: in a spin-echo the T_2^* effect is removed and T_2 is substituted in this equation.

Unlike T_1, T_2 remains relatively unchanged with increasing field strength. It can be measured using a CPMG sequence.

See also BPP equation.

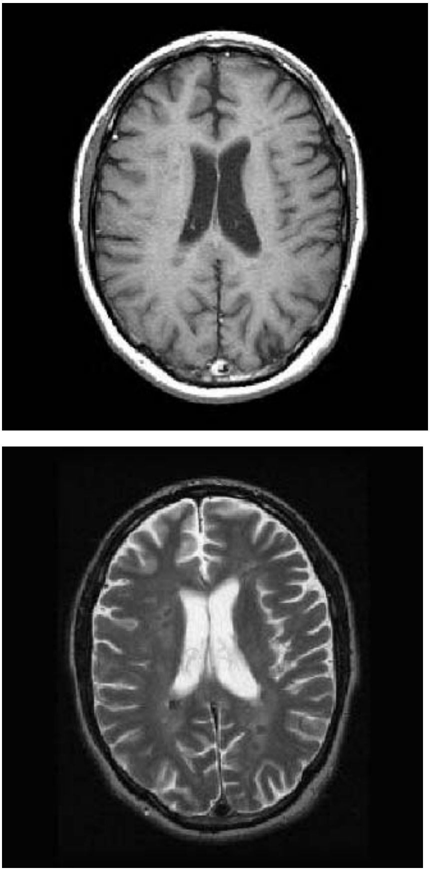


Figure 30. Image **weighting:** Is the water bright or dark? Axial brain images demonstrating T_1 (top, spin-echo TE/TR = 9/380 ms) and T_2 (bottom, fast spin echo TE/TR = 100 ms/4 s) image contrast. Water has long relaxation times leading to **hypointense** and **hyperintense** signal in the CSF, respectively. Compare these to the axial image shown in Figure 2 (spin echo TE/TR =19 ms/3 s), which has a more mixed weighting.

Reference C. S. Poon & R. M. Henkelman (1992). Practical T_2 quantitation for clinical applications. *J. Magn. Reson. Imag.*, **2**, 541–553.

T_2^*

Pronounced 'T-two-star'. This is the effective transverse relaxation time incorporating natural T_2 decay plus the effects of the inhomogeneities of magnetic field (T_2').

$$1/T_2^* = 1/T_2 + 1/T_2'$$

T_2 map

A parameter map or image where the pixel intensity represents the actual transverse relaxation time.

T_2-weighted

Image in which the signal contrast is determined predominantly by differences in T_2 relaxation times. Uses a long TR to minimise T_1-weighting and long TE (e.g. TR $>$ 2 s and TE $>$ 60 ms). See Figure 30.

T_{del}

The temporal resolution of a dynamic (or multi-phase) scan (the delay time).

TE

Time to echo or echo time. The time at which the signal is recorded. See Figure 21 and Figure 28.

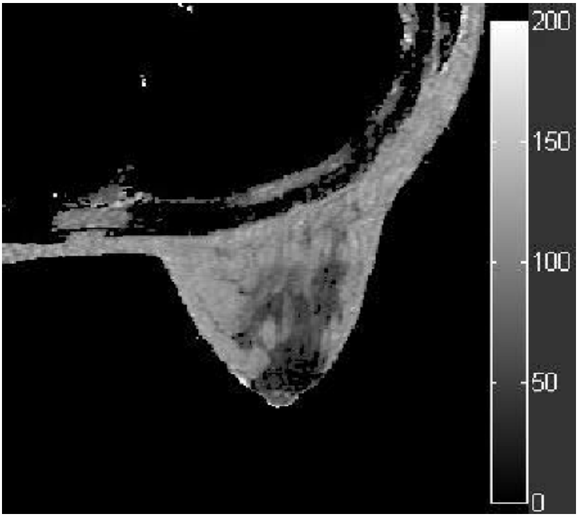


Figure 31. T_2 map. An example of a pixel-by-pixel parameter map demonstrating absolute T_2 relaxation times in the breast (scale in ms).

TE averaging

Method used in MRS for eliminating the phase dependence of *J*-coupled resonances. Signal is collected at many different echo times so that the phase changes average out. May be used to identify or remove J-coupling from the spectrum.

Teleradiology

Viewing and/or reporting medical images (often MRI) at a remote computer workstation.

Temporal resolution

The time interval between successive visits to the same slice or location in a dynamic scan. Typically, a 3-D volume may be acquired every 30 s, while 2-D slices can be imaged every 1–2 s, using fast gradient echo methods. This value will be traded off with higher spatial resolution or improved slice coverage. By combining advanced imaging sequences and parallel imaging technology (e.g. PRESTO and SENSE), a whole brain scan can be achieved in 1 s.

See also dynamic and T_{del}.

Tensor

Full 3-D characterisation of the diffusion coefficient requiring a b = 0 image and at least six other gradient combinations.

See DTI.

Tesla

Relatively large unit of magnetic field compared to the gauss. 1 tesla (T) = 10,000 gauss. The highest magnetic fields produced in laboratories are around 30 T.

Test object

Device used to mimic the patient for quality assurance work.

See also phantom and quality assurance.

Textural analysis

Method by which the subjective interpretation of a MR image can be decomposed into specific quantitative descriptors that take into account the spatial variation and distribution of pixel values.

Reference G. D. Tourassi (1999). Journey toward computer-aided diagnosis: role of image texture analysis. *Radiology*, **213**, 317–320.

TG

Transmitter gain. System setting on GE scanners controlling the power transmitted via the RF coil. Receiver gains are denoted as R_1, R_2 (RG on some systems).

Threshold

The maximum and minimum limits of pixel intensities to be included in some image processing step.

See also segmentation.

THRIVE

T_1 high resolution isotropic volume examination. Philips sequence, using parallel imaging combined with a SPIR 3-D T_1-weighted turbo spin-echo sequence to obtain images of excellent resolution and coverage in short breath-hold examinations.

TI

Time from inversion (also known as time to inspection or inversion time) in an inversion recovery sequence. The interval between the 180° inversion pulse and subsequent 90° pulse to record the signal in the transverse plane.

See also null point and STIR.

Time domain signal

The signal that is detected in the receiver coil prior to fourier transformation into the spatial domain.

Time-of-flight

See TOF.

Time-resolved MRA

Contrast-enhanced MR angiography sequence where 3-D volumes are rapidly acquired so that the arterial and venous phases can be distinguished. Negates the need for accurate bolus timing by acquiring data as quickly as possible.

See also scanning, 4-D, TRICKS.

Tip angle

See flip angle.

TM

The mixing time, in the STEAM spectroscopy sequence.

TMS

The reference compound used in both proton and carbon MRS (tetramethylsilane). Set to 0 ppm. Not to be confused with transcranial magnetic stimulation.

See also ppm scale and MRS.

TNM staging

Common classification system used in cancer staging. Progressive increment of either tumour, node or metastases score indicates worsening of disease stage.

TOF

Time-of-flight. Referring to any flow-related phenomena used in MRA techniques, but used nowadays to describe mainly in-flow enhancement effects.

Reference L. Axel (1984). Blood flow effects in magnetic resonance imaging. *Am. J. Radiol.*, **143**, 1167.

TONE

Tilted optimised non-saturated excitation. Philips/Siemens sequence using a variable flip angle across the imaging plane in order to reduce the saturation effects and increase sensitivity to in-flow enhancement.

TR

Time to Repetition or repetition time. The time of each unit of pulse sequence i.e. the interval between successive excitation pulses. See Figure 21.

See also TE, flip angle.

Trace

A rotationally invariant scalar measurement of the mean diffusivity derived from the diffusion tensor. It is sometimes expressed wrongly as the average apparent diffusion coefficient (ADC) in each imaging direction but is, in fact, given by:

$$\text{Trace} = (\lambda_1 + \lambda_2 + \lambda_3)/3$$

Where $\lambda_1 \ldots \lambda_3$ are the eigenvalues from the diffusion tensor.

See also DTI.

Tractography

Referring to use of diffusion tensor imaging (DTI) to identify the pathway of white matter tracts in the brain. Useful in surgical planning to spare vital fibres. Also used in oncology to decide whether tumours have invaded or displaced white matter.

Reference M. Catani, R. J. Howard, S. Pajevic & D. K. Jones (2002). Virtual in vivo interacrive dissection of white matter fasciculi in the human brain. *NeuroImaging*, **17**, 77–94.

Transceiver

RF coil used as a combined receiver and transmitter for signal detection and excitation, respectively. Examples include many head and all body coils.

Transcranial magnetic stimulation

Method where a hand-held figure-of-eight magnetic coil is placed on the scalp and used to stimulate, or inhibit, functional activation in the brain. May be used in conjunction with fMRI to investigate brain function. MR-compatible TMS coils exist which may be used on the patient *in situ*.

Reference D. E. Bohning, A. Shastri, Z. Nahas *et al.* (1998). Echoplanar BOLD fMRI of brain activation induced by concurrent transcranial magnetic stimulation (TMS). *Invest. Radiol.*, **33**, 336–340.

Transit time

The time interval between the injection of contrast agent and its arrival at the site of interest. Sometimes written as MTT, mean transmit time or τ. Values will be patient dependent (especially in the elderly) and may be determined by using a test bolus. This involves injecting a small amount of contrast agent prior to the proper enhancement study.

Transmitter

RF coil used to only excite the MR signal.

Transmitter reference voltage

System setting on Siemens scanner indicating the transmitter gain, which is adjusted during a pre-scan.

Transverse

Another name for the axial (or transaxial) image orientation.

Transverse plane

Name given to the plane into which the net magnetisation is flipped and where the RF coil is positioned for signal detection. T_2 and $T_2{}^*$ effects in this plane lead to their alternative name of transverse decay. The other important plane in MRI is the longitudinal plane.

Trapezoid

The actual shape of the gradient, due to a finite rise time.

TRICKS

Time resolved imaging of contrast kinetics. GE key-hole imaging sequence, which permits high temporal and spatial resolution of contrasted-enhanced MRI.

Triggering

See gating.

Trigger window

See arrhythmia rejection window.

True FISP

FISP sequence in which the transverse magnetisation is preserved at the end of the TR.

Truncation artefact

Synonym for ringing or Gibbs artefact. It occurs as a result of truncating or under-representing the fourier series due to only a finite number of samples being measured.

The MR signal, may also be said to have been truncated if the receiver is not adjusted properly to accommodate high values, although this is referred to more correctly as data clipping.

TSE

Turbo spin echo. Siemens version of FSE.

Tumour

Solid growth that may be benign or malignant (cancer). The tumour can arise from local cells (primary) or from other sites (metastatic). Common brain tumours include gliomas and astrocytomas (malignant) and meningiomas (benign).

Turbo factor

Synonym for the echo train length in a TSE sequence.

Twin gradients

The design of two separate gradient inserts operating with different linear extents and amplitudes. High gradient amplitude imaging is switched to the smaller-sized gradient coil to prevent PNS.

Two (three)-compartment model

Physiological model used to interpret dynamic contrast-enhanced data. Incorporates compartments for blood, tumour and (additionally) extracellular space. The data shown in Figure 19 has been fitted using a two-compartment model.

See also pharmacokinetic modelling.

Reference P. S. Tofts, G. Brix, D. L. Buckley *et al.* (1999). Estimating kinetic parameters from dynamic contrast-enhanced T_1-weighted MRI of a diffusible tracer: standardised quantities and symbols. *J. Magn. Reson. Imag.*, **10**, 223–232.

Uu

Uniformity

A measure of how homogenous the signal intensity is within the image. The most significant contribution to this is the B_1 profile of the RF coil. Surface coils are very inhomogeneous and produce marked signal variations across the image. Uniformity can be improved using intensity correction algorithms (see SCIC). Uniformity is measured in a floodfill phantom by one of two methods.

(i) Line profile method: a pixel intensity profile is taken across the image (usually an average of ten lines to improve SNR) to demonstrate the uniformity visually. It is advisable to avoid the edges of the phantom if a sphere rather than a cylinder is used. The fractional uniformity can be measured as the number of pixels that are within 10% of the modal value at the centre of the image.

(ii) ROI method: a region is drawn at the centre of the image and the percentage uniformity $\%U$ is defined as:

$$\%U = 100 \times \left(1 - \frac{\sigma}{S}\right)$$

where σ and S are the SD and mean pixel intensity values from the ROI. Perfect uniformity will give a value of 100%.

Reference R. Lerski, J. De Wilde, D. Boyce & J. Ridgeway (1998). Quality control in magnetic resonance imaging, *IPEM Report No. 80.*

USPIO

Ultrasmall super paramagnetic iron oxide contrast agent, with particle size < 50 nm. Used in imaging of the liver, nodal chains, etc.

Vv

Vacuum bore

The use of an evacuated layer in between the gradient coils and patient bore to reduce vibrational noise (see acoustic noise). Approximately 20 dB reduction in volume can be achieved by using this method.

Variable BW

Image sequence where the receiver bandwidth (BW) can be adjusted manually. Note: SNR is inversely proportional to $\sqrt{BW}$. Some scanners specify the bandwidth per pixel or fat–water shift.

Vectorcardiogram

Spatial representation of the magnitude and direction of the cardiac signal. VCG gating permits near 100% accurate cardiac triggering compared to normal ECG gating by using a more reliable *R*-peak detection algorithm.

See also PQRST wave.

Velocity encoding

Method of sensitising the sequence to flow using bipolar gradients.

See phase contrast and VENC.

VEMP

GE sequence abbreviated from variable echo multiplanar.

VENC

The venc is the maximum velocity that will be encoded by the flow sensitive sequence. It is the parameter that adjusts the strength of the bipolar gradient. If this value is set too low, then flow is not visible and vascular plaques will be overestimated. Typical blood velocities are 500 cm/s on exiting the heart, 80–175 cm/s in other arteries and down to 20 cm/s in the veins.

Vent

Airway at the top of scanner through which cryogen gases may exit safely during a quench.

Venetian blind artefact

Artefact seen on 2-D TOF MRA. Occurs due to respiratory motion moving tissue in and out of the slice being saturated.

Ventilation imaging

Imaging of the lung by utilising either hyperpolarised gases (e.g. helium), or 100% oxygen. These gases are inhaled and permit the examination of the lung parenchyma.

Vertigo

Dizzy sensation experienced in fields of 4.0 tesla and above, due to rapid head motion in the scanner bore. Similar effects have been reported near to the entrance of short bore systems at lower field strengths.

See also bioeffects.

VIBE

Volume interpolated body examination, fast breath-hold sequence used in the abdomen

VIBRANT

GE breast sequence, abbreviated from volume imaging for breast assessment. Designed specifically to permit shimming in each separate well of the breast RF coil and permit a high definition bilateral sagittal scan.

VIPR

Vastly undersampled isotropic projection reconstruction. Method of obtaining fast 3-D image data with good temporal resolution and coverage, for example in contrast-enhanced MRA.

Virchow–Robin spaces

Small perivascular spaces in white matter, which become visible at very high field (4.7 tesla).

Virtual endoscopy

Post-processing of 3-D MR data in such a way as to simulate the ‘fly through’ visualisation of real endoscopy. Also referred to as VIE or virtual intraluminal endoscopy.

VINNIE

Velocity imaging in cine mode. Use of dynamically acquired phase-contrast images to image blood flow.

VOI

Volume of interest. A region-of-interest (ROI) in three dimensions.

Voxel

Volume element: pixel with the corresponding slice dimension taken into account. Smallest volume of MRS data.

Voxel bleeding

Signal contamination from adjacent spectroscopic voxels. May be reduced by using a Hanning filter.

Voxel shifting

Retrospective adjustment of the voxel positions during the post-processing of CSI data.

VSS

GE term for their very selective slice technique in MRS. Permits the use of up to ten saturation pulses outside of the voxel of interest to reduce fat or artefact contamination.

Ww

WADA test

Highly invasive procedure where a barbituate is injected into one or other of the carotid arteries to anaesthetise one side of the brain. Tests are then performed to lateralise language function. fMRI is being used increasingly to replace this test.

Wave guides

Entries into the scan room made of frequency-specific length-to-diameter ratio tubes. These prevent RF entering the scan room but allow equipment to be passed into the room.

Wash in (out)

The rate at which contrast is taken up (and excreted) by tissue. Important in the differentiation of benign and malignant tumours.

See also angiogenesis and pharmacokinetic modelling.

Water

Principal source of proton signal. Vastly more concentrated than other metabolites, hence water suppression is needed in MRS. It has a characteristic resonance of 4.7 ppm.

Water suppression

The removal of the water resonance using a CHESS pulse centred on the main proton frequency. Used mainly in MRS to

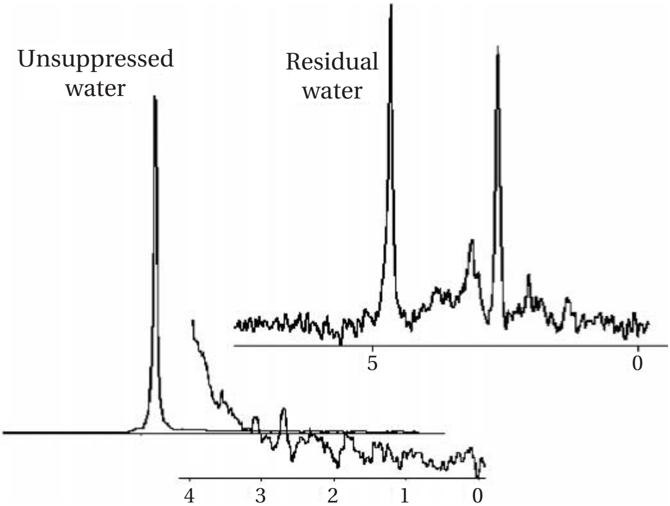


Figure 32. Water suppression. Water dominates proton MRS masking signal from low concentration metabolites (shown inset 0–4 ppm). After reducing the water by 400-fold, the metabolites are easily detected. There is often still enough residual water to reference the chemical shift range.

permit the discrimination of important metabolites present at extremely low concentrations.

WEFT

Water elimination fourier transform. Method of suppressing water used in MRS. Works by performing an inversion recovery pulse on the water peak followed by excitation of the remaining metabolites as the water reaches its null point.

Weinmann data

Measurement of blood plasma concentration of Gd-DTPA over time. Used in pharmacokinetic modelling of contrast enhanced data.

Reference H. J. Weinmann, M. Laniado & W. Mutzel (1984). Pharmacokinetics of Gd-DTPA/dimeglumine after intravenous injection into healthy volunteers. *Physiol. Chem. Phys. Med. NMR*, **16**, 167–172.

Whisper gradients

Name of the GE gradient noise reduction scheme involving a vacuum lined bore.

White blood

Referring to any MRA technique in which blood (flow) appears brighter than stationary tissue.

See in-flow enhancement.

Whole-body

Said of high-field scanners, which are also able to scan anatomy outside the head (i.e. 'whole body capable' rather than 'head only').

Whole-body screening

Refers to an MRI examination in which a complete head-to-foot investigation is performed (for example to examine metastatic spread), using the body coil or separately selectable coil elements. Utilises a moving table technique.

Width

Window width.

See windowing.

Windowing

To manipulate the range of pixel values displayed in an image to best show the image contrast and detail. Pixel values are not processed and 'lost' but only the user-specified range are displayed on screen. Usually both the window width and level are specified. Window width is the range of pixel intensities that are displayed as screen brightness and is related to image contrast. Window level is the mid-point of the window width and determines brightness. Most scanners adjust the window settings automatically following image acquisition but this may require fine-tuning by the operator, especially when the background signal (or noise) is being viewed.

See also threshold.

Xx

Xenon

The isotope ^{129}Xe may be used in hyperpolarised gas imaging.

x-direction

Direction that is perpendicular to the main magnetic field orientation, and is chosen conventionally as the left–right direction. See Figure **??**.

Yy

Y-direction

Direction that is perpendicular to the main magnetic field orientation, and chosen conventionally as the anterior–posterior direction. See Figure **??**.

Zz

■ *Z*-direction

The head–foot imaging direction, or parallel to the main magnetic field. See Figure **??**.

■ Z-score

Statistic used in fMRI analysis. Essentially, tests how similar the means of two distributions are (e.g. task versus rest images).

See also correlation coefficient.

■ Zeeman levels

The quantised energy states that arise in nuclei (or electrons) when they are placed in a magnetic field. See Figure 22.

See quantum number.

■ Zero filling

Method of appending zeros at the end of the time domain signal to improve the frequency resolution of the spectrum. For example, a spectrum acquired with 1024 data points may be zero-filled to 2048 points.

See MRS.

■ Zeugmatography

From the Greek word *Zeugma* (meaning joining together). Archaic term used first by Lauterbur to describe the

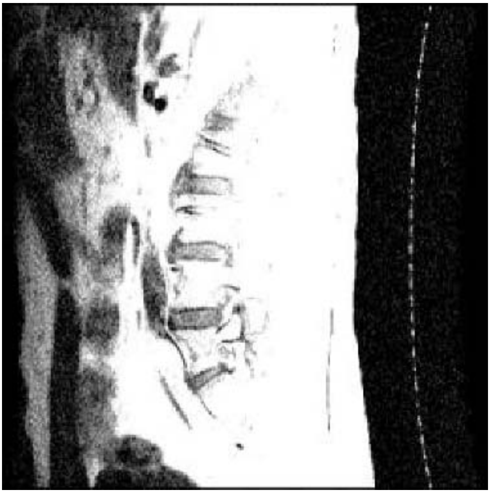


Figure 33. RF or zipper artefact is seen to the right of this spine image.

combination of a static and RF magnetic field in order to produce MR images.

ZIP

Zerofill interpolation processing, used to obtain images artificially at a higher matrix size, e.g. 1024 from 512 data.

Zipper artefact

Zip-like artefact along the frequency-encoding direction caused by RF interference. The position and width of the artefact identifies the frequency and bandwidth of the likely source. Also, more correctly referred to as an RF artefact.

Zoom gradients

See twin gradients.

Zoom imaging

Philips technique for ultra-fast real-time imaging. Utilises a very small FOV, reduced *k*-space and fast scanning techniques to image rapidly at high resolution. The 90° and 180° pulses are applied perpendicular to each other to overcome phase wrap.

Appendices

Appendix I
MR-related constants

Constant	Symbol	Value (units)	Equation
Magnetogyric ratio	γ	42.58[†] MHz/T	$\omega_0 = \gamma B_0$ Frequency of precession
Permeability of free space	μ_0	$4\pi \times 10^{-7}$ H m^{-1}	$\mu = B/H$ Ratio of flux density in a sample to the external field
Boltzmann constant	k	1.381×10^{-23} J K^{-1}	$\Delta n = n\gamma \hbar B_0/2kT$ Difference in spin populations
Electron charge	e	1.602×10^{-19} C	$\mu = e/2\, m_e . J$ Magnetic moment
Electron mass	m_e	9.109×10^{-31} kg	$\mu = e/2\, m_e . J$ Magnetic moment
Proton mass	m_p	1.673×10^{-27} kg	$\mu = e/2\, m_p . J$ Magnetic moment
Neutron mass	m_n	1.675×10^{-27} kg	
Planck constant	h	6.626×10^{-34} J s	$\Delta E = \hbar\omega_0$ Energy difference between spin up/down

[†] This is the value for proton only; for other nuclei see Appendix II.

Appendix II Properties of MR visible nuclei

Nucleus	I	Abundance (%)	Sensitivity	γ (MHz/T)
^{1}H	½	99.98	1.0000	42.58
^{2}H	½	0.02	0.0097	6.53
^{13}C	½	1.11	0.0160	10.71
^{19}F	½	100	0.8300	40.05
^{23}Na	3/2	100	0.0093	11.26
^{31}P	½	100	0.0660	17.23

Appendix III Bloch equations

The behaviour of net magnetisation M when placed in an external magnetic field B is described as:

$$\frac{dM}{dt} = \gamma [M \times B]$$

This is modified in the presence of relaxation effects (T_1 and T_2) to give:

$$\frac{dM_z}{dt} = (M_0 - M_z)\,T_1$$
$$\frac{dM_{x,y}}{dt} = M_{x,y}/\,T_2$$

The solutions are as follows:

$$M_x = e^{-t/T2} \cos \omega_0 t$$
$$M_y = e^{-t/T2} \sin \omega_0 t$$
$$M_x = M_0(1 - e^{-t/T1})$$

which describes a spiral precession about B.

The evolution of the net magnetisation (and the x,y,z components), following the removal of the 90° excitation pulse, is shown in the diagram below:

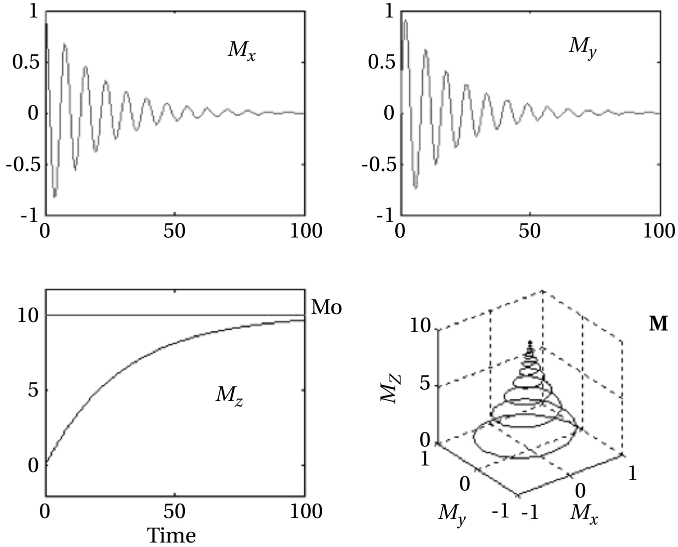


Figure A.1. Courtesy of R. Garcia-Alvarez.

Appendix IV Some tissue relaxation times

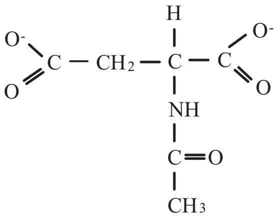
Tissue	T_1 (ms)	T_2 (ms)
CSF	2060	–
Grey matter	1100	90
Muscle	1075	33
Breast tissue	$774 \pm 183^{\dagger}$	$56 \pm 12^{\dagger}$
White matter	560	80
Fat	$227 \pm 42^{\dagger}$	$119 \pm 5^{\dagger}$

All values are at 1.5 tesla.
† Author's own experimental values.

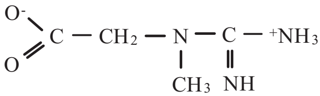
Appendix V Useful fourier transform pairs

$\boldsymbol{S}(t)$	$\Leftrightarrow$	$\boldsymbol{S}(\omega)$
Sinc		Rectangular
$\sin(\pi T\omega)/\pi T\omega$		distribution
Sinusoid		Delta (single frequency)
Gaussian		Gaussian
$\exp(-\pi t^2)$		$\exp(-\pi\omega^2)$
Exponential (FID)		Lorenzian
$\exp(-t/\mathrm{T}_2)$		$T_2/(1+(2\pi\mathrm{T}_2\omega)^2)$
Rectangular		Sinc

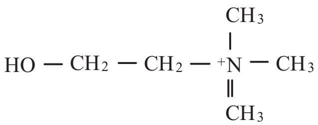
Appendix VI Structure of some common MR molecules



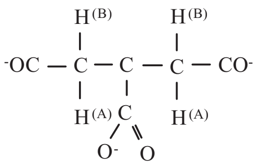
N-Acetyl asparate



Creatine

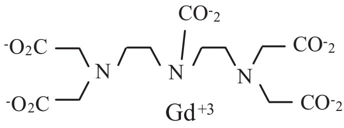


Choline



Citrate

Note: The positions of the two protons that are strongly coupled and give citrate its charcteristic four-peak resonance are labelled A and B.



Gd-DTPA

Note: This charged complex is called gadopentetate. In Gd-DTPA each molecule of this is balanced with two moles of meglumine (+1 charge) to give the compound the name gadopentetate dimeglumine.

Appendix VII
Further reading

Some selected textbooks that I would also recommend.

A. D. Elster & J. H. Burdette (2001). *Questions and Answers in Magnetic Resonance Imaging*. St Louis, MO: Mosby.

A comprehensive text written in the form of frequently asked questions concerning much of MRI and MRS.

D. W. McRobbie, R. E. A. Moore, M. J. Graves & M. R. Prince. (2003). *MRI from Picture to Proton*. Cambridge: Cambridge University Press.

Written in an informal easy-to-read style. Very informative textbook.

R. K. Harris (1986). Nuclear Magnetic Resonance Spectroscopy. Avon: Longman.

Advanced MR spectroscopy textbook.

Shellock, F. G. (2001). Magnetic Resonance Procedures: Health Effects and Safety. FL: CRC Press.

Extremely well-sourced summary of the main safety issues surrounding MRI.

P. Jezzard, R. M. Matthews & S. M. Smith (eds.). (2001). *Functional Magnetic Resonance Imaging: An Introductory Guide*. Oxford: Oxford University Press.

Detailed textbook covering all aspects of functional MRI.

P. Tofts (2003). *Quantitative MRI of the Brain*. Chichester, UK: Wiley.

Chapters from various contributors covering each quantitative measurement in MRI. Excellent read.

Appendix VIII Greek letters

Upper	Lower	Name	Where you've seen them used . . .
Α	α	Alpha	Spin-up state, flip angles
Β	β	Beta	Spin-down state, minor angles
Γ	γ	Gamma	Magnetogyric ratio
Δ	δ	Delta	Chemical shift
Ε	ϵ	Epsilon	Permittivity
Ζ	ζ	Zeta	
Η	η	Eta	
Θ	θ	Theta	Flip angles, phase angles
Ι	ι	Iota	
Κ	κ	Kappa	Some constants
Λ	λ	Lambda	Wavelength
Μ	μ	Mu	Magnetic moment, permeability
Ν	ν	Nu	Frequency
Ξ	ξ	Xi	
Ο	ο	Omicron	
Π	π	Pi	Relating radians and angles
Ρ	ρ	Rho	Spin density
Σ	σ	Sigma	Shielding constant
Τ	τ	Tau	Inter-pulse times, correlation time
Υ	υ	Upsilon	
Φ	ϕ	Phi	Usually phase angles
Χ	χ	Chi	Susceptibility
ψ	ψ	Psi	Wave function (quantum mechanics)
Ω	ω	Omega	Frequency