Educational course: Imaging Acquisition & Reconstruction

Pulse Sequence Modules I (IR, DE, Spatial SAT & Chem SAT)

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Highlights:

- Contrast-preparation pulse-sequence modules provide a flexible means to achieve a variety of useful contrast behaviors in MRI.
- Inversion-recovery contrast preparation is useful for obtaining strong T1-weighted contrast or for suppressing the signal from one or more tissues based on their associated T1 relaxation times.
- Driven-equilibrium contrast preparation can provide T2-weighted contrast, even for short-TR gradient-echo acquisitions, and is useful for imparting motion sensitivity for applications such as diffusion or vessel-wall imaging.
- Presaturation contrast preparations are used to suppress the signal from a selected region, such as moving tissue that would otherwise result in motion artifacts, or from a selected chemical species, such as fat.

Target audience: Researchers and clinicians interested in basic methods for manipulating image contrast in MR pulse sequences.

Objective: Describe the implementation and characteristics of four commonly-used approaches for controlling the image contrast generated by MR pulse sequences.

Contrast-preparation modules: An essential task of nearly every MR pulse sequence is to generate signal intensities for tissues in the image that vary in relation to some selected property of the tissues, such as their T1 or T2 relaxation times. This variation in signal intensity with tissue property allows one to distinguish one tissue from another, thereby creating contrast in the image. For some pulse sequences, for example T1-weighted conventional spin-echo, repetition of the basic pulse-sequence events (in this case, excitation [90° RF pulse], refocusing [180° RF pulse] and acquisition of spatially-encoded data), as required to collect the data necessary to form an image, also results in the desired image contrast. For this example, the repetition time TR is chosen to be shorter than T1 relaxation times of interest so that the longitudinal magnetization associated with the tissues cannot completely recover between repetitions, leading to signal intensities in the image which vary inversely with T1 relaxation time (i.e., tissues with relatively short relaxation times appear bright and those with relatively long relaxation times appear dark). Nonetheless, the desired contrast behavior often cannot be obtained using only the basic pulse sequence itself. In these cases, a separate contrast-preparation "module," typically applied immediately prior to the excitation RF pulse(s) for the pulse sequence, may be useful. The contrast-preparation module contains some combination of RF pulses, magnetic field gradients, and time delays. Herein, four commonly-used contrast-preparation modules are described:

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inversion recovery, driven equilibrium, spatially-selective presaturation and chemically-selective presaturation.

Inversion recovery: An "inversion" RF pulse is an RF pulse, having a (net) flip angle of 180°, that is used to rotate longitudinal magnetization from alignment with the positive z axis (i.e., the direction of the main static magnetic field) to alignment with the negative z axis. The term "inversion recovery" (abbreviated IR) refers to the process wherein the inverted longitudinal magnetization "recovers," via T1 relaxation, towards its associated thermal equilibrium value M_0 (see Fig. 1). The time evolution of the longitudinal magnetization M_Z following inversion from thermal equilibrium is given by the familiar expression:

$$M_Z(t) = M_0\left(1 - 2e^{-t/T1}\right). \quad [1]$$

Prior to the development of MR imaging, inversion recovery was already commonly used in NMR spectroscopy for applications such as measuring T1 relaxation times. While inversion recovery is also used in MR imaging for measurement of T1 relaxation times [1,2], there are several other important applications, as described briefly below.

Implementation: An inversion-recovery contrast-preparation module consists of an inversion RF pulse, which may be spatially selective (i.e., applied in conjunction with one or more magnetic field gradients), non-spatially selective, or chemically selective (see section below on spatially-selective or chemically-selective presaturation, *Practical considerations*), depending on the requirements of the application, followed by a time delay during which the magnetization relaxes toward thermal equilibrium, as described above. The time period between the inversion RF pulse and the subsequent excitation RF pulse of the pulse sequence is called the "inversion time" or "time to inversion," and is typically denoted by the abbreviation TI. In practice, "spoiler" or "crusher" gradient pulses (i.e., magnetic field gradient pulses that have a large moment [duration times amplitude] relative to other gradient pulses used in the pulse sequence) are often applied along one or more axes, immediately following the inversion RF pulse, to dephase any transverse magnetization generated because the RF pulse did not achieve the desired 180° flip angle or, for the case of a spatially-selective inversion RF pulse, generated at the transition regions (edges) of the inverted slab.

Applications: Inversion-recovery contrast preparation is commonly used to achieve strong T1-weighted image contrast, or to suppress the signal from a specific tissue type based on its T1 relaxation time (see Fig. 1). Compared to the degree of T1-dependent contrast that can be obtained from relaxation following a 90° RF pulse, as used to create T1-weighted images for spin-echo or fast/turbo spin-echo pulse sequences, substantially stronger T1 weighting can be obtained using an inversion-recovery preparation. While, in general, the amount by which contrast is increased for inversion recovery compared to saturation recovery (i.e., recovery following a 90° RF pulse) depends on the relaxation times and proton densities of the tissues, the maximum signal difference between two tissues for inversion recovery is double that for saturation recovery when the proton densities of the tissues are equal. Inversion-recovery contrast preparation to achieve strong T1 weighting has been used in a variety of pulse-sequence types, particularly magnetization-prepared gradient-echo methods [3,4].

As illustrated in Fig. 1, there is a specific time following inversion wherein the longitudinal magnetization for any given tissue equals zero. If the TI is chosen to equal this value, such that the excitation RF pulse is applied when the longitudinal magnetization for the tissue is zero, the

tissue will produce no signal in the image (it will appear black), and is thus said to be "nulled" [5,6]. The TI for tissue nulling is easy to calculate from Eq. [1] as the T1 value times the natural logarithm of 2 (0.69T1; the appropriate TI will be somewhat shorter if the magnetization is not at thermal equilibrium when inverted). Two very common applications of this principle include STIR (abbreviation for short TI inversion recovery or short tau inversion recovery) [5], wherein the TI is chosen so that the signal from fat is nulled, and FLAIR (abbreviation for fluid attenuated inversion recovery) [6], wherein the TI is chosen so that the signal from fluid, especially cerebrospinal fluid, is nulled. A contrast preparation that includes multiple inversion RF pulses can be used to suppress more than one tissue in the image. For example, a double-inversion preparation is often used to suppress cerebrospinal fluid and either white or grey matter in the brain, to permit selective imaging of either grey or white matter, respectively [7].

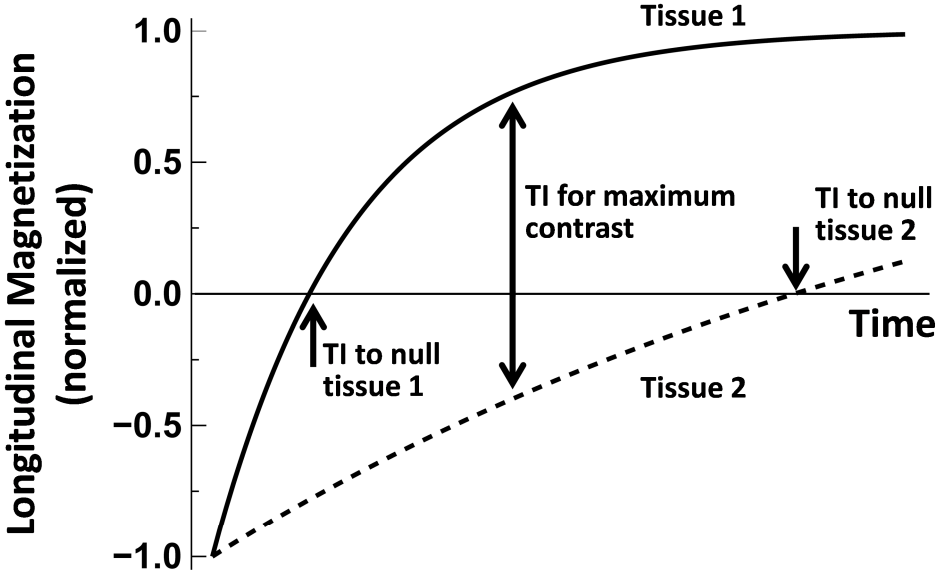

Figure 1. Inversion-recovery curves for tissues with relatively short (solid line) and relatively long (dashed line) T1 relaxation times.

Inversion RF pulses are used in a number of other important contrast preparations, such as the double-inversion black-blood preparation [8] for cardiac or vascular imaging, and as part of the tagging scheme for certain approaches to perfusion imaging [9,10].

Practical considerations: An important practical consideration for inversion-recovery preparation is the fidelity of inversion (achieving a 180° flip angle) over the volume of interest. A number of experimental factors, such as transmitter miscalibration, transmit RF-field (B1+) inhomogeneity, and static field inhomogeneity, can result in flip angles other than 180° from the RF pulse. In particular, simple amplitude-modulated RF pulses, as typically used for spatially-selective excitation or refocusing, yield a flip angle that is directly proportional to the applied B1 value. Thus, for example, if B1 deviates by 10% from its intended value for some reason, the RF-pulse flip angle will likewise be 10% off. To address this common problem, RF pulses designed to produce the desired effect on the magnetization (e.g., inversion) even in the presence of substantial B1 variation, such as composite [11] or adiabatic [12] RF pulses, are usually used in

commercial implementations of inversion-recovery contrast-preparation modules. To deal with flip-angle variations caused by static field inhomogeneity [e.g., 13], it is important for the inversion RF pulses to have a sufficiently high transmit bandwidth relative to expected static field inhomogeneity.

Driven equilibrium: Analogous to inversion recovery, driven-equilibrium (abbreviated DE) contrast preparation has its roots in NMR spectroscopy. The "driven equilibrium Fourier transform," or DEFT, method [14] was developed to improve the efficiency of spectroscopic measurements for substances with long T1 and T2 relaxation times. Given transverse magnetization generated by a 90° excitation RF pulse (Fig. 2a-b), the driven-equilibrium approach entails applying a 180° refocusing RF pulse (Fig. 2c-d) at a time delay (τ) following excitation, to form a spin echo (Fig. 2e) at a time equal to twice the time delay (2τ), and then applying a second 90° RF pulse with appropriate phase to rotate the magnetization back along the positive z axis (Fig. 2f). In other words, the second 90° RF pulse "drives" the magnetization back toward its thermal equilibrium value. The second 90° RF pulse is sometimes called a "restore," "flip-back," or "tip-up" pulse. The important aspect of this process is that, when the time period between the first and second 90° RF pulses is short compared to the T1 relaxation time, the magnitude of the longitudinal magnetization immediately following the second 90° RF pulse is much larger than that which would be obtained by omitting the second 90° RF pulse and simply allowing T1 relaxation to occur. In fact, considering the intervening 180° RF pulse, which acts as an inversion RF pulse for any longitudinal magnetization existing just before the pulse is applied, the magnitude of the longitudinal magnetization just before the second 90° RF pulse is close to zero for relatively long T1 relaxation times.

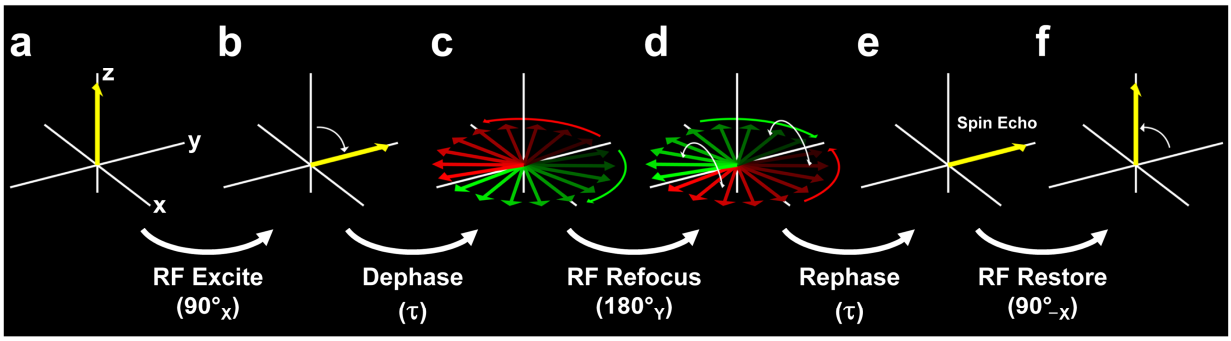

Figure 2. Magnetization vector diagram illustrating a driven-equilibrium (90°-180°-90°) preparation. Yellow vectors represent the total magnetization for a voxel, and red and green vectors represent magnetization associated with regions within the voxel which experience different resonance frequencies due to static field inhomogeneity or applied magnetic field gradients. For simplicity, relaxation is neglected in the diagrams.

Implementation: The simplest approach for implementing a driven-equilibrium contrast-preparation module is to use $90°_X$, $180°_Y$ and $90°_{-X}$ "hard" (rectangular waveform) RF pulses, separated by intervening time delays of equal duration, followed by spoiler (crusher) gradient pulses applied along one or more axes, immediately following the second 90° RF pulse. However, for the reasons discussed briefly in the *Practical considerations* section above for inversion recovery, simple, amplitude-modulated RF pulses often do not achieve the desired 90° or 180° flip angles, resulting in poor performance of the preparation (e.g., intensity shading in the

image [15]). Thus, implementations based on composite [16] or adiabatic [17] RF pulses were developed to obtain more robust performance in the presence of RF- or static-field inhomogeneity. The composite-pulse implementation of ref. 16 also used a series of 180° refocusing RF pulses, instead of one, to further improve practical performance of the preparation.

Applications: Probably the most common early use of driven-equilibrium contrast preparation was to generate longitudinal magnetization encoded with T2 weighting. That is, at the end of the preparation, the magnitude of the longitudinal magnetization is proportional to the T2 value of the tissue. This use of driven-equilibrium contrast preparation, often called "T2 preparation" or simply "T2 prep," was applied in the context of magnetization-prepared gradient-echo pulse sequences [3,15,16]. This application is a good example of when the preparation module provides image contrast that could not be effectively obtained using the basic pulse sequence itself (short TR gradient echo). It was also recognized that adding gradient pulses during each of the two time delays to generate sensitivity to motion, such as diffusion [18] or flow, could be useful. Applications of motion-sensitive driven-equilibrium contrast preparation have increased substantially in recent years [19-21], particularly for suppressing the signal from flowing blood to provide improved visualization of vessel wall pathology [19,20].

A variant of the driven-equilibrium preparation is driven inversion, wherein the phase of the second 90° RF pulse is modified so that the magnetization is returned to the negative z axis, instead of the positive z axis [22]. An interesting application of driven inversion is FLAIR imaging, where use of a driven-inversion preparation, instead of just an inversion pulse, permits increased signal-to-noise ratio for white and grey matter while maintaining good cerebrospinal fluid suppression [23].

The basic concept of driven-equilibrium preparation is also widely used in fast/turbo spin-echo pulse sequences to permit high signals from fluid to be obtained even when the repetition time is relatively short. For this implementation, a 90° RF pulse with appropriate phase is applied at the end of each CPMG echo train, at the time when an echo forms following the last refocusing RF pulse of the train.

Spatially-selective or chemically-selective presaturation: These two contrast-preparation modules are discussed together because the basic concepts for the two techniques and the associated pulse-sequence implementations are very similar. Recall that the term "saturation" refers to the situation wherein RF is applied to eliminate the longitudinal magnetization, thereby resulting in equal nuclear spin populations for the spin-up and spin-down states. "Presaturation" means that the longitudinal magnetization is driven to zero just before some other pulse-sequence event of interest, typically the excitation RF pulse for the pulse sequence. Presaturation is commonly used to suppress the longitudinal magnetization within a selected region [24,25] (spatially-selective presaturation, also known by terms such as spatial SAT or PRESAT) or to suppress the longitudinal magnetization for a chemical species with a specific chemical shift [26] (chemically-selective presaturation, also known by terms such as chem SAT, FATSAT or CHESS [chemical-shift selective or chemically-selective suppression] pulses).

Implementation: In MRI, presaturation is typically achieved by simply applying a 90° RF pulse. This pulse of course generates transverse magnetization, which is then dephased using spoiler (crusher) gradient pulses applied along one or more axes, immediately following the 90° RF pulse. Thus, when the subsequent excitation RF pulse is applied, there is (essentially) no longitudinal magnetization for the region or chemical species of interest to be converted into transverse

magnetization by the excitation RF pulse, and the transverse magnetization associated with the region or chemical species of interest is sufficiently dephased so that it will not produce an echo when imaging data is collected. As a result, the presaturation contrast-preparation module, consisting of a 90° RF pulse followed by spoiler gradient pulses, suppresses the signal from the region or chemical species of interest, so that the region or chemical species appears dark in the image.

For spatially-selective presaturation, the RF pulse is spatially-selective so that it affects a specific region within the volume being imaged as chosen by the user. The RF pulses are typically selective along one direction, but it is possible to employ RF pulses that are spatially selective in two or three dimensions [27,28]. Most commercial MR scanners allow the user to specify multiple spatial presaturation regions.

For chemically-selective presaturation, the RF pulse is frequency-selective so that it affects only the narrow band of frequencies associated with the resonance frequency of the chemical species to be suppressed. Typically, a relatively long amplitude-modulated RF pulse is used, although other pulse configurations, such as a composite RF pulse, are also suitable. It is also possible to use specially designed RF pulses that permit one to suppress the magnetization for a chosen chemical species within a specific region [29], combining spatially-selective and chemically-selective presaturation; these are called spatial-spectral RF pulses.

Applications: Spatially-selective presaturation is commonly used for two purposes: (1) to suppress aliasing (wrap-around) artifacts from regions for which the signal would otherwise wrap into the desired field of view, and overlay the anatomy of interest, given the selected spatial-encoding parameters, or (2) to suppress signal from tissues that would otherwise result in motion artifacts in the image. Examples of the second application include: presaturating the signal from the region of the face (mouth, tongue) to suppress motion artifacts from this region in cervical spine imaging; presaturating the signal from the anterior abdominal wall to suppress breathing-induced motion artifacts when imaging the abdomen; and presaturating the blood signals upstream of a slice of interest to suppress motion artifacts from pulsatile blood flow.

Chemically-selective presaturation is most commonly used to suppress the signal from fat (fat saturation or FATSAT), but can also be used in other ways, such as to suppress the signal from water or, for breast imaging applications, to suppress the signal from silicone.

Practical considerations: Given the finite durations of the presaturation and subsequent excitation RF pulses, and the time required for application of spoiler gradient pulses following the presaturation RF pulse, there is naturally some regrowth of longitudinal magnetization associated with the tissues to be suppressed by the time that the excitation RF pulse is applied, especially for tissues with a short T1 relaxation time such as fat. For this reason, a flip angle slightly larger than 90° is often used for the presaturation RF pulse so that the longitudinal magnetization is initially negative, and passes though (or at least close to) zero when the excitation RF pulse is applied, analogous to the concept of tissue nulling for inversion recovery as discussed above. Technically, when the flip angle is larger than 90°, the preparation is no longer presaturation, although in practice the same names are often used for the methods. For applications in which complete saturation of the magnetization is critical, adiabatic RF pulses, or a short series of RF pulses separated by spoiler gradients, may be used in the presaturation module.

For both spatially-selective and chemically-selective presaturation, homogeneity of the static magnetic field is a key determinant of technique performance. For spatially-selective

presaturation, static field inhomogeneity that is substantial relative to the bandwidth of the RF pulse causes a spatial mismatch between the desired region of signal suppression and the achieved region. For chemically-selective presaturation, field inhomogeneity that is large relative to the chemical shifts between the species to be suppressed and those for other species of interest results in lack of suppression for certain regions in the image and, potentially, unintended suppression of the species to be imaged. (For example, for fat suppression applied in a region associated with marked field inhomogeneity, the water signal may be suppressed instead of the fat signal.) In addition, chemically-selective fat suppression is technically challenging at relatively low magnetic field strengths (<< 1T) because the resonance-frequency separation decreases in proportion to field strength. (Thus, STIR is preferred for fat suppression at relatively low magnetic field strengths.)

For fat suppression, another variant of the chemically-selective preparation is important. This variant, referred to by acronyms such as SPAIR or SPECIAL, replaces the frequency-selective presaturation RF pulse with a frequency-selective inversion RF pulse, which may also be adiabatic, and the time period between the inversion and excitation RF pulses is chosen so that the inverted fat magnetization passes through zero when the excitation RF pulse is applied, analogous to STIR [30]. For certain applications, this approach provides more robust suppression of the fat signal then the basic chemically-selective presaturation method.

Conclusion: Contrast-preparation pulse-sequence modules provide a flexible means to achieve a variety of useful contrast behaviors in MRI. The four contrast-preparation modules described herein are used commonly in clinical MRI to achieve strong T1 weighting or selectively suppress signal based on T1 (inversion recovery), to obtain T2-weighting or sensitivity to motion (driven equilibrium), or to suppress MR signals associated with a specific region (spatially-selective presaturation) or chemical species (chemically-selective presaturation).

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