Spoiled & Balanced Gradient-Echo Sequences

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Objectives of this Presentation

- Offer intuitive understanding of signals in rapid gradient-echo sequences
- Enable accurate numerical simulation of signals in rapid gradient-echo sequences
- Provide insight into how different sequences may be used clinically

Presentation Outline

Basic GRE Sequences

Gradient-echo (GRE) sequences are generally any sequences that do not specifically use spin echoes, and consist of repeated RF excitations, normally with a constant flip angle (α), followed by imaging (Fig. 1)[1]. Two broad groups of GRE sequences are common. In the first group, the repetition time (TR) is much greater than the T2 relaxation time, which may include common BOLD acquisition sequences (long TR), ultra-short TE sequences used to measure signal from short-T2 species, or other intermediate cases. The signal dynamics in this group are fairly easily analyzed, and typically offer proton-density or T2* weighting, with some amount of T1 weighting.

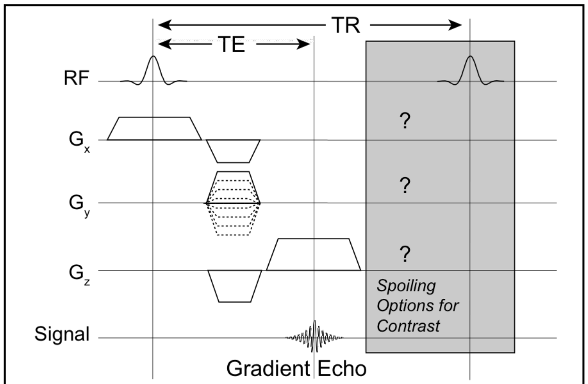

Figure 1: *A rapid gradient-echo (GRE) sequence uses repeated RF excitation pulses and imaging gradients. Spoiling and balanced variations affect the signal and contrast characteristics.*

The second group of sequences, where TR is short compared to T1 and T2 requires more complicated signal analysis because both non-equilibrium longitudinal and transverse magnetization persist over multiple TR intervals[2,3]. These sequences can be further divided by the type of spoiling used – balanced (no spoiling), gradient-spoiled, and RF spoiled. The signal characteristics of common sequences in both groups are described in more detail here.

Long-TR Gradient Echo Sequences

The simplest group of GRE sequences to analyze are those where TR is long compared to T2*, so that it can be assumed that any transverse magnetization dies out before the next RF excitation pulse. The signal is analyzed very simply by examining the T1 recovery over TR, and assuming this reaches a steady state prior to each RF excitation pulse. This group commonly includes GRE sequences used for functional MRI, typically with blood-oxygen-level-dependent (BOLD) contrast, as well as ultrashort echo-time imaging (UTE) sequences used to image very short T2 species such as cortical bone, meniscus or certain tissue components in myelin.

Balanced Steady-State Free-Precession (bSSFP, TrueFISP, FIESTA, Balanced FFE)

In bSSFP sequences, the imaging and slice-selection gradients are carefully rewound or balanced so that the net gradient area over one TR is zero on all axes (Fig. 2) [4,5]. In signal formation, the effect of gradients is usually ignored. For short TR, the signal is a strong function of flip angle, T1, T2, TR, TE and resonance frequency offset (Δf), and is easily solved analytically or numerically. At moderate-to-high flip angles, the periodic signal vs. resonance frequency offset (Δf) profile has signal nulls that cause "dark-band" or "banding" artifacts at frequencies that are integer multiples of 1/TR[6]. Adding a constantly increasing phase ("phase cycling") to the RF excitations shifts the signal vs. resonance frequency plot, and typically adding 180º of phase is used in most imaging scenarios, to ensure high signal on-resonance. Multiple acquisitions with different phase cycling can be combined to give a more uniform signal vs. Δf profile, at a cost of scan time[7]. The bSSFP contrast is a function of T2/T1, and though the signal profile is complicated, the effect of Δf and flip angle α can be combined into a single "effective flip angle," which can help with intuitive understanding of the steady state[8].

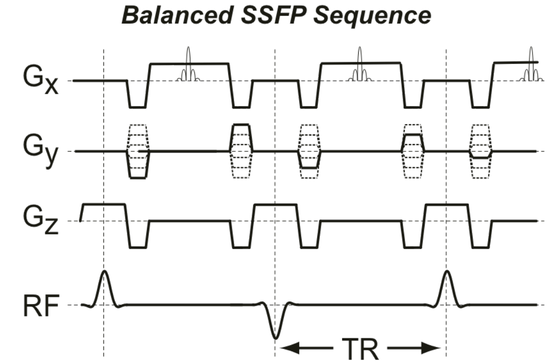

Figure 2: *A balanced SSFP sequence has fully-rewound ("balanced") gradients on all axes. The sign of the RF pulse is often alternated to produce a high signal on-resonance.*

Gradient-Spoiled Echo (GRE, FISP, FFE, GRASS)

Adding a constant unbalanced gradient on each TR results in gradient spoiling (Fig. 3). The spoiler area is typically chosen to impart an integer number of cycles across a voxel, and this effectively averages the signal over one or more periods of the bSSFP signal vs. resonance frequency profile, since the gradient induces a known (and ideally constant) precession over each TR[9]. Gradient-spoiled imaging results in lower signal than bSSFP, but avoids the sensitivity to background magnetic field. The contrast remains a function of T2/T1, and in practice these sequences exhibit some diffusion sensitivity[10]. In most gradient-spoiled sequences, the spoiling follows image acquisition, and the signal characteristics appear as if at the start of a bSSFP repetition. Alternatively, playing a spoiler gradient *before* image acquisition alters the signal characteristics to increase T2 weighting, often termed PSIF or CE-FAST imaging[11].

RF-Spoiled Gradient-Echo (T1-FFE, FLASH, SPGR)

RF spoiling is the most commonly used approach for rapid T1-weighted imaging[12]. RF spoiling combines gradient spoiling with a quadratic phase increment of the RF pulse, for example $\varphi_n = 117^{\circ}\, n^2/2$, where φ is the RF phase angle and n is the repetition number[13]. The effect of RF spoiling is to minimize residual transverse magnetization at the end of each repetition, resulting in contrast that is similar to what would be achieved if transverse magnetization could be completely eliminated, simply pure T1 contrast. In terms of bSSFP signal dynamics, RF-spoiling results in a continuously shifting signal profile in both time and space, though this interpretation may offer limited practical benefit.

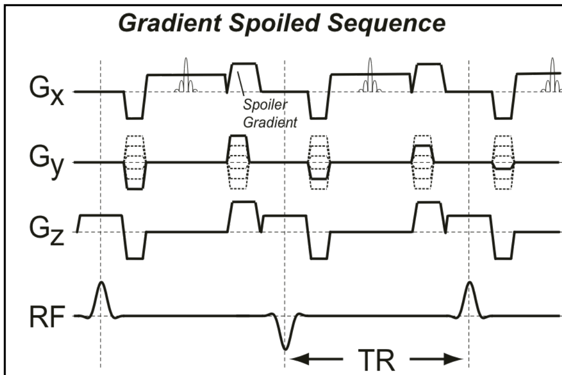

Figure 3: *A gradient-spoiled sequence is similar to balanced SSFP sequences, but includes a non-balanced gradient or spoiler. RF-spoiled sequences use the same gradient pattern, but further modify the phase of the excitation pulses.*

Calculations

Calculation of signal and contrast levels is important in analyzing and understanding different pulse sequences. While analytic expressions have been derived for many of the sequences above, numerical calculations are often of equal value. A simple Bloch-equation simulation can often model effects of relaxation, precession and diffusion. For sequences with constant gradient spoiling, including many variants of the common sequences described above, the extended-phase-graph (EPG) formalism is very useful[14]. The EPG approach works whenever the gradient "twist" over a repetition can be quantized, and elegantly decomposes the signal into a Fourier basis that offers an alternate approach to propagating magnetization states through a sequence of pulses.

Applications and Examples

Numerous applications of gradient-echo sequences are common. The short repetition times and steady states are ideal for 3D imaging without artifacts from signal modulation across k-space that can hamper spin-echo-train sequences. Rapid imaging following the injection of a contrast agent typically uses RF-spoiled gradient-recalled imaging. Balanced SSFP is common for cardiac imaging as it offers high contrast between myocardium and blood, while also offering desirable high signal from flowing blood. Sequences are often combined with magnetization-preparation blocks, which may include fat saturation, background suppression, T2-prep for enhanced T2 contrast, or myocardial tagging.

Additional Information

Several related publications and sources may be helpful in learning about spoiled and balanced gradient-echo imaging. This talk will overlap somewhat with recent review articles on the topic[15,16]. An excellent introductory article links steady-state gradient-echo sequences to extended phase graphs[17]. Prior lectures by Matthias Weigel and Karla Miller during the 2010 ISMRM Weekend Educational Sessions offer excellent and concise descriptions of extended phase graphs and their application to gradient-echo sequences, respectively.

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