Allen D. Elster, MD

Gradient-Echo MR Imaging: Techniques and Acronyms[1]

This overview briefly traces the history and nomenclature of gradient-recalled-echo (GRE) techniques used in magnetic resonance (MR) imaging. GRE sequences, which are now offered commercially by 11 major manufacturers of MR imagers, are presented to illustrate their structural similarities and subtle differences in implementation. A classification scheme is proposed for these sequences employing a vendor-independent nomenclature. A glossary of GRE abbreviations and acronyms found in the current MR marketplace also is presented.

Index terms: Magnetic resonance (MR) • Magnetic resonance (MR), pulse sequences • Magnetic resonance (MR), technology • State-of-art reviews

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THROUGHOUT most of the 1980s, spin-echo (SE) techniques dominated the daily practice of clinical magnetic resonance (MR) imaging. By the middle of the decade, however, interest began to be directed toward a new class of pulse sequences, which used gradient echoes (GREs). Whereas SEs were produced by *pairs* of radio-frequency (RF) pulses, GREs were formed by *single* RF pulses in conjunction with gradient field reversals.

In the 1990s, GRE techniques have become an essential component of the modern MR examination, being offered as standard software by every major vendor. Because these sequences have demonstrated great clinical utility in so many diverse settings, a relatively large number of GRE variations have been developed. Unfortunately, no uniform system of nomenclature for these sequences has yet been adopted. As a consequence, almost 40 different names, abbreviations, and acronyms for GRE imaging sequences have been devised by vendors to differentiate and market their products.

In this overview the history of GRE imaging will be briefly recounted. I will describe the major varieties of GRE techniques in common use and propose a unified, vendor-independent classification scheme for these sequences. Where not restricted by confidentiality agreements, I will also illustrate some of the subtle variations in GRE sequence design unique to certain brands of imagers, which may result in slight differences in their imaging behavior. As a final contribution, I have constructed a modern lexicon for GRE terminology, which will make possible a rapid comparison of GRE sequences available in the current MR market (Tables 1, 2).

HISTORY OF GRE NOMENCLATURE

Although the phenomenon of "nuclear induction" was first demonstrated by Bloch et al (1) and Purcell et al (2) in 1946, it was not until 1950 that Hahn (3) recorded the transient MR signal after an RF pulse that we now call the FID. Later that same year, Hahn reported the discovery of a remarkable new type of MR signal, the SE, which could be generated by application of two successive RF pulses (4). Hahn and others also recognized that a train of three or more RF pulses could produce a third type of MR signal called a stimulated echo (4,5).

In 1958, Carr (6) first analyzed what happens when a long series of closely spaced ($\tau \ll T2$) RF pulses is applied to a sample (Fig 1). In this scenario, FID signals will occur after each RF pulse and SEs will be produced by successive pairs of RF pulses. Each set of three or more RF pulses will in turn produce stimulated echoes, which coincide with the SEs when the RF pulses are evenly spaced and no gradients are applied for imaging. Moreover, if the series of RF pulses is applied sufficiently rapidly, the tails of the FIDs and SEs will merge together so that a continuous signal of varying amplitude is produced, and a steady-state free precession will have become established.

During the 1950s it became increasingly recognized that MR signals could not only be generated by additional RF pulses but also by manipulations of the main magnetic field (7). In 1960, Hahn formally proposed using magnetic field reversals to induce MR echoes in sea water (8). Abragam, in his classic 1961 monograph, *The Prin-*

[1] From the Department of Radiology, Bowman Gray School of Medicine, Wake Forest University, Medical Center Blvd, Winston-Salem, NC 27157-1022. Received March 13, 1992; revision requested May 15; final revision received August 6; accepted September 10. The author is supported in part by the RSNA Research and Education Fund as a Winthrop/RSNA Scholar. **Address reprint requests to** the author.

Abbreviations: FID = free induction decay, FISP = fast imaging with steady-state precession, FLASH = fast low-angle shot, GRE = gradient echo, MP-GRE = magnetization-prepared gradient echo, RF = radio frequency, SE = spin echo, SS-GRE = steady-state gradient echo, SS-SE = steady-state spin echo, TE = echo time, TR = repetition time.

Table 1
Comparison of GRE Pulse Sequence Names by Vendor

Manufacturer	"Basic" GRE (GRE)	Steady-State (SS-GRE-FID)	Steady-State (SS-GRE-SE)	Spoiled GRE (SP-GRE)	Magnetization Prepared (MP-GRE)
Elscint (Hackensack, NJ)	...	F-SHORT	E-SHORT	SHORT	Turbo-SHORT*
GE Medical Systems (Milwaukee, Wis)	MPGR (1.5 T), FS (0.5 T)	GRASS	SSFP	SPGR	FSPGR-prepared, FGR-prepared
Hitachi Medical (Tarrytown, NY)	GFE	GFE	...	GFE	RS*
Instrumentarium Imaging (Milwaukee, Wis)	...	...	...	PS	...
Otsuka Electronics (Fort Collins, Colo)	FE	FFE	...	...	...
Philips Medical Systems (Shelton, Conn)	...	FFE	CE-FEE-T2	CE-FFE-T1	TFE*, FASTSCAN
Picker International (High-land Hts, Ohio)	FE, FESUM, FEDIF	FAST	CE-FAST	RF-FAST, T1-FAST	RAM-FAST*
Resonex (Sunnyvale, Calif)	GRECHO	...	...	...	...
Shimadzu Medical Systems (Gardena, Calif)	STAGE	SSFP	STERF	STAGE	SMASH
Siemens Medical Systems (Iselin, NJ)	...	FISP	PSIF	FLASH	TurboFLASH*, MP-RAGE (3D)
Toshiba America Medical Systems (Tustin, Calif)	PFI, FE	FE	...	...	Turbo-FE*

Note.—FID = free induction decay, SS = steady state.
* Sequences with preparatory pulses are not yet commercially available.

ciples of Nuclear Magnetism (9), explicitly described the feasibility of generating an echo by field or gradient reversal. Using the analogy of runners who reverse their direction halfway through a race, Abragam referred to these gradient reversal echoes as "racetrack echoes." Abragam had some doubts about the general utility of this method of echo formation, however, stating, "the point of spoiling a very homogeneous field . . . [by gradient reversals] . . . may appear questionable" (9).

During the 1960s and early 1970s, pulse sequences based on SEs largely continued to dominate the MR literature, although research continued on gradient manipulations of the MR signal and steady-state free precession phenomena (10–13). Nevertheless, interest in GRE signal formation largely floundered until 1976, when Mansfield and Maudsley (14) proposed their revolutionary "fast scan imaging." This new method, a forerunner of modern echo-planar techniques, used gradient reversals to generate echoes (15). In 1976, Hinshaw (16) also developed a steady-state imaging method, which was subsequently implemented in two dimensions and presented in 1981 at the Bowman Gray International Symposium on NMR Imaging (17,18). By the early 1980s, several additional university- and industry-based researchers had developed their own variations of GRE imaging (19,20). On the first Technicare MR imagers, these

Table 2
Acronyms Used in GRE Imaging

Acronym	Explanation and Manufacturer
CE-FAST	Contrast-enhanced FAST (Picker)
CE-FFE-T1	Contrast-enhanced fast field echo with T1 weighting (Philips)
CE-FFE-T2	Contrast-enhanced fast field echo with T2 weighting (Philips)
E-SHORT	SS-GRE with SE sampling (Elscint)
FAST	Fourier-acquired steady state (Picker)
FE	Field echo (Otsuka, Picker, Philips, Toshiba)
FEDIF	Field echo with echo time (TE) set for water/fat signals in opposition (Picker)
FEER	Field even echo by reversal (Picker)
FESUM	Field echo with TE set for water and fat signals in phase (Picker)
FFE	Fast field echo (Philips)
FGR	Fast GRASS (GE Medical Systems)
FISP	Fast imaging with steady-state precision (Siemens)
FLASH	Fast low-angle shot (Siemens)
FRE	Field reversal echo (Picker)
FS	Fast scan (GE Medical Systems)
F-SHORT	SS-GRE with FID sampling (Elscint)
FSPGR	Fast spoiled GRASS (GE Medical Systems)
GFE	Gradient field echo (Hitachi)
GFEC	Gradient field echo compensation (Hitachi)
GRASS	Gradient recalled acquisition in the steady state (GE Medical Systems)
GRE	Gradient echo, gradient-recalled echo
GRECHO	Gradient recalled echo (Resonex)
MPGR	Multiplanar GRASS (GE Medical Systems)
MP-RAGE	Magnetization-prepared rapid GRE (Siemens)
PFI	Partial flip angle (Toshiba)
PS	Partial saturation (Instrumentarium)
PSIF	Reversed FISP (Siemens)
RAM-FAST	Rapidly acquired magnetization-prepared FAST (Picker)
RF-FAST	RF-spoiled FAST (Picker)
RS	Rapid scan (Hitachi)
SHORT	Elscint term for any fast GRE sequence
SMASH	Short minimum angle shot (Shimadzu)
SPGR	Spoiled GRASS (GE Medical Systems)
SSFP	Steady-state free precession (GE Medical Systems, Shimadzu, Toshiba)
STAGE	Small tip angle GRE (Shimadzu)
STERF	Steady-state technique with refocused FID (Shimadzu)
T1-FAST	FAST with T1 contrast (gradient-spoiled) (Picker)
TFE	Turbo field echo (Philips)
Turbo-FE	Turbo field echo (Philips)
TurboFLASH	Turbo version of FLASH (Siemens)
Turbo-SHORT	Turbo version of SHORT (Elscint)

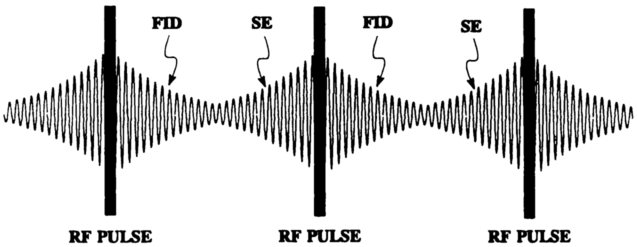

Figure 1. A steady-state free precession results when a series of closely spaced RF pulses are applied to a sample. The resultant signal is composed of both FID (free induction decay) and SE (spin echo/stimulated echo) components.

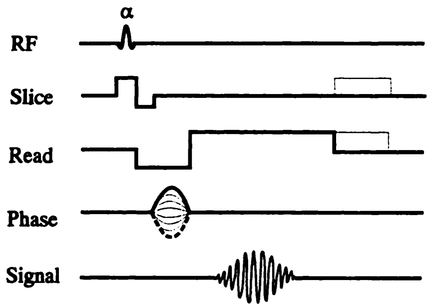

Figure 2. The "basic" GRE sequence. See text for details. Dotted gradients along slice-select (section-select) and read provide for resonant-offset averaging.

echoes were referred to as "gradient-recalled echoes"; on the early imagers from Picker, they were called "field reversal echoes" (FREs). Because of field inhomogeneities and gradient power limitations in these early imagers, however, SE techniques gradually supplanted the initial GRE methods, providing images of markedly superior quality and reproducibility.

By 1983, no official nomenclature had yet been adopted for GRE techniques. In the first *Glossary of NMR Terms* (21) published by the American College of Radiology, the terms "gradient echo" and "field echo" (which were both in common usage at the time) do not even appear. Only the mere existence of these techniques was acknowledged briefly under the definitions of "rephasing gradient" and "spin echo," where they were referred to as "time reversal echoes."

Shortly thereafter, interest in GRE imaging was rekindled by a group of German researchers under the direction of A. Haase and J. Frahm, who proposed the FLASH (*f*ast *l*ow-*a*ngle *sh*ot) technique (22). FLASH was unique compared to previous GRE methods in two major respects: (*a*) Its gradient structure was specifically designed to produce spoiling or disruption of transverse coherences, thereby allowing spin-density– or T1-weighted images to be obtained, and (*b*) it used RF flip angles of less than 90°, reducing saturation effects and providing another variable with which to manipulate image contrast. Shortly thereafter, several other groups of investigators proposed GRE techniques that used low flip angle pulses but whose gradient structure preserved transverse coherences (FAST, Fourier-acquired steady state technique; FISP, fast imaging with steady-state precession; and GRASS, gradient-recalled acquisition in the steady state) (23–29). Confusion immediately began to arise, however, since the structures of these sequences were under constant revision, often being modified substantially while their original names were retained. Perhaps the best example of this phenomenon is the evolutionary changes experienced by the FLASH and FISP sequences, whose current commercial implementations as Siemens products only remotely resemble their initial descriptions in the scientific literature from the mid-1980s.

Since 1986, we have witnessed an explosive growth in the number and complexity of GRE pulse sequences. Today, the major manufacturers of MR imagers offer nearly 40 GRE variants, each with a different name or clever acronym selected for marketing purposes. I will now attempt to describe how each of these GRE sequences works, categorizing them into functionally similar groups and proposing a vendor-independent nomenclature. Because it is not possible to provide a comprehensive mathematical analysis of these sequences in the limited space available, the interested reader is referred to several excellent technical reviews that have recently been published (30–36).

THE "BASIC" GRE SEQUENCE

The most basic of all GRE techniques offered by commercial vendors today has a structure similar to that of a conventional SE sequence, except that the 180° refocusing pulse is missing. As the timing diagram (Fig 2) for such a sequence illustrates, a single RF pulse (with arbitrary tip angle α) is first applied to a section (which has been selected by simultaneous activation of the section-selection [also known as "slice-selection"] gradient). Dephasing of spins into a frequency-dependent spatial pattern is provided by the first negative (downward)–going lobe of the read gradient in Figure 2. Subsequently, the positive-(upward)–going lobe of the same gradient reverses this dispersion of spins, resulting in their refocusing into a GRE. Spatial encoding by phase is provided by applying different strengths of phase-encode gradient during each RF cycle. This "basic" GRE sequence is identical in structure to the original FLASH sequence proposed by Haase et al (22). The reader should note, however, that the "FLASH" sequence offered as a product by Siemens has undergone several modifications and refinements and thus can no longer be classified as a "basic" GRE technique.

The fundamental differences between GRE and SE imaging are addressed in numerous textbooks and review articles (31,32,37–40). Gradient refocusing of the MR signal corrects only for phase shifts induced by the action of the gradient itself. Specifically, phase shifts resulting from field inhomogeneities, static tissue susceptibility gradients, and chemical shifts are not canceled at the center of the GRE as they are in the ideal SE experiment. The transverse decay of the GRE signal is therefore determined by the *effective* spin-spin relaxation time (T2*), which is a reflection of both "true" T2 and inhomogeneity effects. Unwanted phase dispersions by means of T2* processes may be minimized by using small voxels and short TEs (41).

Commercial implementations of the "basic" GRE sequence are available on most imagers and are offered under familiar names such as MPGR, FE, and PFI (Table 1). The relative simplicity of this sequence makes it easily adapted for such features as cardiac gating, gradient-moment nulling, and three-dimensional Fourier transform (3DFT) acquisition. Most manufacturers who offer this basic GRE sequence also permit the user to adjust the RF flip angle (α). Manipulation of the RF flip angle allows one to obtain unique image contrasts, as well as to alter the level of equilibrium magnetization.

The potential advantages of partial flip angle MR imaging have been thoroughly described in numerous technical and clinical reports (37,38, 42). Because of fundamental trigonometric properties, a small flip angle (α) pulse may create an appreciable transverse magnetization while disturbing the longitudinal magnetization only slightly (Fig 3). For example, a 15° RF pulse acting on a magnetization **M** initially aligned in the z direction creates a transverse component of size (sin 15°) × *M*, or 0.26*M*. Meanwhile, the longitudinal component along the z axis has barely been disturbed, reduced only 3% to (cos 15°) × *M*, or 0.97*M*. The fact that the longitudinal magnetization has been largely preserved means that little saturation has occurred; for short TR sequences, a significantly stronger MR signal may thus be obtained by using small flip angle (rather than 90°) RF pulses.

At first it may seem paradoxical that reducing the flip angle (and hence the fraction of longitudinal magnetization deflected into the transverse plane) would result in a stronger MR signal than could be obtained by using 90° pulses. One must realize, however, that the magnetization tipped to create the MR signal arises from the steady-state longitudinal magnetization (M_z) that exists immediately before each RF pulse. The signal obtained from a fast GRE sequence thus represents a "balancing act" between factors that maintain the steady-state longitudinal magnetization and those that increase the fraction of magnetization that is tipped into the transverse plane. In general, therefore, the MR signal in the "basic" GRE sequence will not be maximized at $\alpha = 90°$ but at a value known as the Ernst angle, which depends on the ratio TR/T1 (where TR = repetition time) and is typically much smaller than 90° (11,12).

So far, our simplified analysis of the action of the RF pulse (Fig 3) has assumed that the steady-state magnetization **M** has no net transverse component (ie, **M** is aligned with the z axis at the time of the RF pulse). Both the basic GRE sequence and the spoiled GRE sequence (discussed subsequently) generally satisfy this assumption and can be classified as *incoherent* steady-state techniques. The term "incoherent" implies that only a longitudinal steady state has been established (ie, the transverse components are dispersed in phase and are incoherent).

Under special conditions, however, a *coherent* steady state may become established, in which both the longitudinal and transverse components reach a steady state. In this situation, the steady-state magnetization **M** is not strictly aligned with the z axis but also has a projection in the transverse plane. Pulse sequences that generate this coherent steady-state signal will be called SS-GRE sequences and are discussed in greater detail below. As we will describe, special structuring of the gradient waveforms must be performed in order to maintain this coherent steady state. Furthermore, the signal behavior, image contrast, and optimal flip angle for these sequences will depend not only on TR/T1, but also on T2 and a new variable (β), the angle through which the spin precesses in the transverse plane between two consecutive RF pulses. The angle β is called the resonant offset angle, phase angle, or precession angle (Fig 4a). The value of β will typically vary with position and depend on multiple local factors including the net effect of imaging gradients, static field inhomogeneities, and the transmitted phase of the RF pulse (35). Figure 4b illustrates graphically how an α° RF pulse affects a given spin depending on the resonant offset angle of that spin.

As long as our prototype "basic" GRE sequence is operated in a multisection mode with relatively long TR values (providing intrinsic "spoiling" or disruption of transverse coherences), resonant offset effects prove to be of little concern. If operated in a single-section mode with short TR values (eg, TR < 150 msec), however, an uncontrolled partial steady-state free precession may become established (27,30). Position-dependent clustering of resonant offset angles may then occur. If such a position-dependent distribution of resonant offset angles exists across a section at the end of a cycle, then the next RF pulse will have an effect on this signal that is also position-dependent (43). As a result, bands of varying signal intensity ("FLASH bands") may appear, which significantly degrade the final image.

The practical method to reduce these resonant-offset artifacts is to extend the duration of the read gradient following echo collection (dotted lines, Fig 2). The read gradient is left on long enough to ensure that a full range of resonant offset angles (from 0° to 360°) exists across each voxel (44). This uniform integration of signal prior to the next RF pulse means that contribution to the steady-state magnetization will be averaged or smoothed over a full range of resonant offsets. Accordingly, position-dependent variations in phase and signal intensity will be minimized. Haacke and Tkach (34) have recommended that the term "resonant offset averaged steady state (ROAST)" be applied to such methods. While I prefer to avoid the adoption of yet another acronym, the phrase "resonant offset averaging" is a very good one and is appropriately descriptive of this process. Prolongation of the readout gradient to accomplish resonant offset averaging is apparently used by all manufacturers who offer the basic GRE sequence as an option (eg, Picker's FE sequences). As a mi-

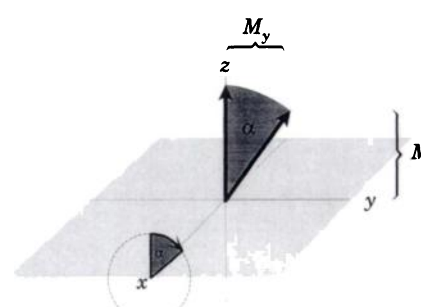

Figure 3. A small flip angle pulse (α) may generate an appreciable transverse component of magnetization (M_y) while disturbing the longitudinal component (M_z) only slightly.

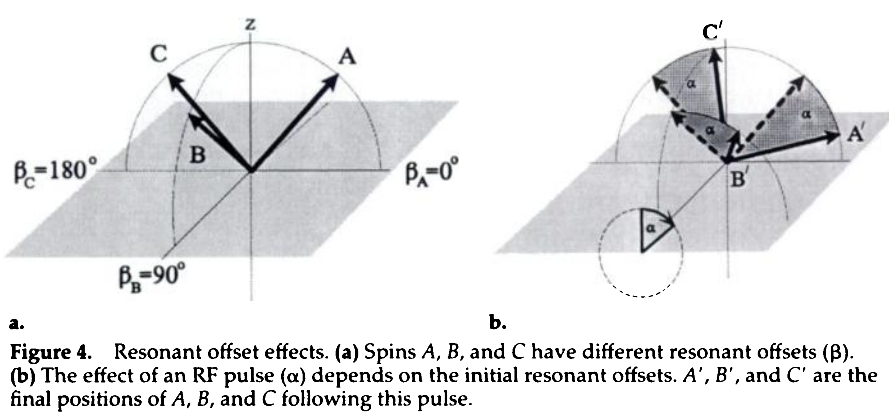

Figure 4. Resonant offset effects. **(a)** Spins *A*, *B*, and *C* have different resonant offsets (β). **(b)** The effect of an RF pulse (α) depends on the initial resonant offsets. *A′*, *B′*, and *C′* are the final positions of *A*, *B*, and *C* following this pulse.

nor variation, some manufacturers will also apply a second constant dephasing gradient along the section-select axis to provide resonant offset averaging within the plane of the section (eg, GE Medical Systems' MPGR sequence).

In practice, the basic GRE sequence is operated in the multisection mode with values of TR sufficiently long so that transverse coherences are effectively averaged out or disrupted (spoiled). When used under these conditions, the basic GRE sequence will display image contrast similar to that of the spoiled GRE sequence discussed below. For this reason, not all manufacturers offer the basic GRE sequence we have described, but rather provide gradient- or RF-spoiled GRE techniques, which can also be used in long TR, multisection applications. No matter which method is employed, the equilibrium signal obtained will be proportional to spin density, modified by the effects of T2* relaxation and T1 saturation. Increased T2* contrast sensitivity is obtained principally by lengthening TE. T1 saturation effects are regulated by flip angle and TR (45).

STEADY-STATE (SS)–GRE SEQUENCES

SS-GRE sequences are designed to operate in either single-section or multisection modes by using extremely short TR values (eg, TR < 50 msec) and to produce a coherent steady-state free precession. This steady state is controlled and maintained in two ways: (*a*) through the use of resonant offset averaging on the read and section-select gradients (as in the basic GRE sequence) and (*b*) through the application of rewinder gradients on the phase-encode axis, discussed in detail below.

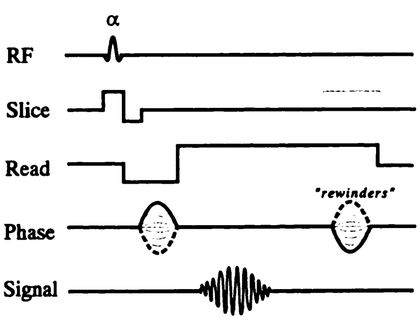

Figure 5. Steady-state GRE sequence with FID sampling (SS-GRE-FID). See text for details.

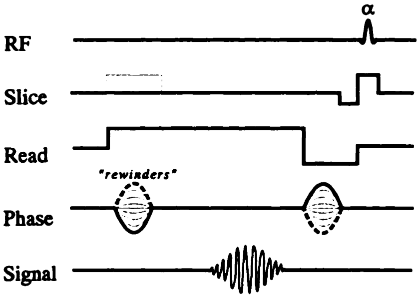

Figure 6. Steady-state GRE sequence with SE sampling (SS-GRE-SE). See text for details.

Recall that the steady-state signal can be considered to be the sum of two components: an FID occurring early in the cycle (just after each RF pulse) and a stimulated echo/SE occurring late in the cycle (just before the next RF pulse). In theory it should be possible to recover both signals simultaneously and coherently, provided that the gradient profiles are perfectly balanced (the so-called original or true FISP experiment) (29). In practice, however, unpredictable phase errors make this perfect balance difficult to achieve (46,47). Accordingly, all steady-state sequences commercially available today sample (by GRE formation) either the FID or the stimulated echo/SE components, but not both. It should be noted, however, that Siemens has developed a method to extract both signals simultaneously by collecting pairs of echoes acquired with and without phase alternation of the RF (48); thus, it is likely that "true FISP" will be available as a commercial product in the near future (Laub G, personal communication).

SS-GRE Sequences with FID Sampling

Coherent steady-state sequences that sample the FID component are among the most widely used of all GRE techniques and are implemented in a nearly identical fashion by every manufacturer. Familiar names for these sequences include GRASS, FISP, FAST, and FFE (Table 2). The structure of these sequences is similar to that of the basic GRE technique previously described. A prototype SS-GRE-FID sequence modeled after Picker's FAST sequence is shown in Figure 5. Note that the imaging gradients have been purposely left unbalanced along both the section-select and read axes to produce resonant offset averaging (and hence artifact reduction). Also observe that the phase-encode gradient pulses have been applied twice per cycle, the second time with reversed polarity. These second phase-encode gradient steps are known as rewinders, and their purpose is to ensure stability of the phase of the MR signal in each repetition interval and to aid the development of coherent transverse magnetization (32). Without these rewinders, resonant offsets would vary from cycle to cycle (since the phase-encode step changes). Phase-encoded information in one cycle could spill over into the next cycle, generating unwanted stimulated echoes or interference (FLASH) bands across the image.

Image contrast for a small flip angle SS-GRE-FID sequence exhibits the same proportionality to spin-density and T2* effects as the basic GRE sequence. However, because steady-state longitudinal and transverse components of magnetization exist at the end of each cycle, repetitive RF pulses cause a "mixing" or exchange of magnetization among the components (49). Mathematical analysis of these effects predicts that image contrast will also depend in a complicated manner on flip angle, T1, T2, and T2/T1, as well as RF phase relationships and the net effect of imaging gradients (50–54). As the flip angle is increased, signal behavior and image contrast are primarily determined by T2/T1.

SS-GRE Sequences with SE Sampling

GRE sequences that sample the SE (and stimulated echo) components of the coherent steady-state signal have a pulse timing diagram (Fig 6) that is a mirror image of the SS-GRE FID sequence. This "time reversal" of gradient applications is reflected in the acronym Siemens uses for this sequence, PSIF (which is just a reversal of the letters in FISP). GE Medical Systems calls their version of this sequence SSFP (which could really apply to any short TR sequence). Elscint refers to their sequence as E-SHORT; the "E" presumably refers to recording of the spin/stimulated *e*cho component of the steady-state signal. In our vendor-independent nomenclature, we will refer to this sequence as SS-GRE-SE.

Because the echo appears to occur *before* the RF pulse in the timing diagram, it is not immediately apparent how an echo is created at all by this unusual sequence. Indeed, if the sequence were run for only one cycle, no echo would be recorded. When one studies phase relationships over two cycles, however, an echo will be produced from magnetization brought down into the transverse plane by an RF pulse in the preceding cycle. The effective echo time is thus TR plus TE, since an entire additional cycle (of length TR) has passed prior to echo collection. This relatively long evolutionary period before echo collection allows for natural transverse decay of the magnetization to occur. Images from the SS-SE-FID sequence thus appear to have a dominant "T2-like" weighting. Because T2 contrast is apparently "enhanced" by this technique, the acronym "contrast-enhanced FAST," or CE-FAST, was the original name given to this sequence (55), and it has been retained by Picker for the name of their commercial version. The "contrast-enhanced" concept of T2 weighting is also reflected in the acronym used by Philips: CE-FFE-T2.

SPOILED GRE TECHNIQUES

The term "spoiling" refers to the purposeful disruption of transverse coherences that persist from cycle to cycle (32). All MR manufacturers now offer some form of spoiled-GRE (SP-GRE) sequence as part of their commercial packages (Table 1). Familiar names include FLASH, SPGR, RF-FAST, and T1-FAST.

While the final images produced by these sequences may appear nearly identical, several different spoiling methods (49) are used by the various MR vendors (Fig 7). Siemens' FLASH technique involves the application of variable spoiler gradients along the section-select axis. The amplitude of these spoilers is varied linearly from view to view in the Siemens product, whereas some other manufacturers use a gradient "look-up" table containing an array of optimized values.

In 1989, GE Medical Systems applied a different spoiling strategy with the release of its SPGR sequence. In this technique, the phase of the RF carrier is semirandomly changed from view to view, effectively preventing the buildup of transverse phase coherences. In theory at least, RF spoiling is superior to variable gradient amplitude spoiling in that it is spatially invariant and does not generate eddy currents.

Picker has also implemented an RF spoiling technique on their new line of MR systems, called RF-FAST. This technique is very similar to SPGR, but it uses a different algorithm for selecting RF phase offsets. Picker also retains a second type of spoiled GRE sequence on many of its lower-field-strength systems called T1-FAST, which is a gradient-spoiled technique similar to Siemens' FLASH.

Elscint, Instrumentarium, and Siemens have developed their own techniques for RF spoiling, which can be implemented on imagers that do not have digitally controlled RF amplifier subsystems. Although representatives from each company have been reluctant to reveal the details of their methods, the RF spoiling is apparently achieved following the method of Zur et al (49) by allowing semirandom phase shifts of the RF oscillator to accumulate between views, thus preventing the buildup of transverse coherences.

RAPID (PREPARED) GRE SEQUENCES

If an SS-GRE sequence is run with very short TR values (ie, TR $\leq$ T2*), neither a longitudinal nor a transverse steady state has enough time to become fully established during the course of an imaging experiment (36). Because image acquisition has not taken place under steady-state conditions, nonuniform weighting of the data along the phase-encoded axes will occur. Loss of image resolution along this direction results. Furthermore, because the TR values are so short, small flip angles must be used to minimize saturation and to preserve the signal-to-noise ratio. As a result, image contrast in these sequences is dominated by spin-density effects and is thus relatively poor. Rapid GRE sequences typically demonstrate inadequate contrast between soft tissues of similar composition and are thus not very sensitive in the detection of pathologic abnormalities. In spite of these potential drawbacks, the overwhelming benefit of imaging speed has made the rapid GRE sequence a viable technique.

The simplest form of rapid GRE sequence is merely an SS-GRE-FID technique run with very short TR values. This type of sequence is suitable for breath-hold abdominal studies and for dynamic contrast material–enhanced studies performed to measure perfusion (56). Several vendors offer this simplest form of rapid GRE sequence (eg, Picker's RAM-FAST, Philips' Turbo FFE, Siemens' Turbo-FLASH).

Although rapid GRE sequences generally produce images with relatively poor tissue contrasts, interesting T1 or T2 contrast behavior may be restored by applying a preparatory pulse (or pulses) in the interval before

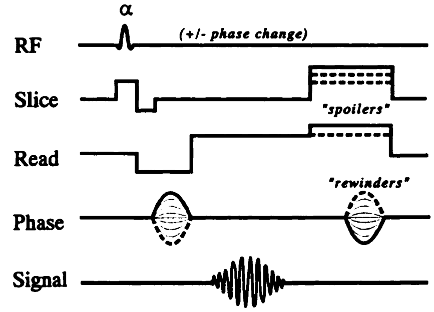

Figure 7. Spoiled GRE sequence. See text for details.

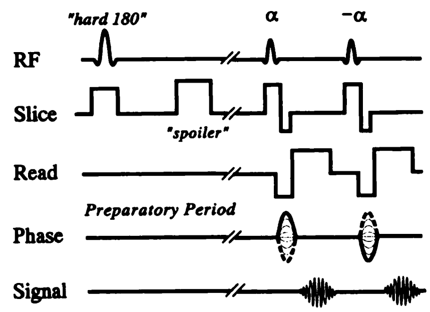

Figure 8. Magnetization prepared GRE sequence (MP-GRE). See text for details.

data collection is begun. I will refer to sequences modified in this fashion as *magnetization-prepared* GRE (MP-GRE) techniques. Both Siemens and GE Medical Systems currently offer MP-GRE sequences as commercially available products, marketed under the familiar names of MP-RAGE and fast-SPGR-prepared, respectively.

The simplest preparatory pulse is simply a nonselective ("hard") 180° pulse, which inverts the tissue magnetization across the sample (57,58). After an inversion time delay, a rapid SS-GRE-FID sequence is performed, as illustrated in Figure 8. Image contrast is determined by the effective inversion time delay for this sequence, which is the time interval between the 180° pulse and the central phase-encoding step. Because the longitudinal magnetization (and hence T1 contrast) may be changing during the MP-GRE sequence, it is potentially important to be able to have control over the ordering of the phase-encode steps. Final image contrast will depend on the precise order in which the phase-encode lines have been sampled (56). Additionally, if rapid T1 relaxation occurs during data acquisition, segmentation of the total sequence into several steps, including waiting periods, may be necessary.

By changing the preparatory period to 90°/180°/−90° set of pulses, T2 contrast can be obtained (59). This is the so-called driven equilibrium version of the sequence. Other preparatory period variations are possible including schemes to produce stimulated echoes, magnetization transfer effects, chemical shift effects, and diffusion sensitization (60,61). An exuberant growth in MP-GRE sequences over the next few years is anticipated, with many new variations and names forthcoming. Whatever distinctions once existed between rapid GRE and echo-planar techniques will likely continue to fade away as new fast imaging strategies are developed that combine features of both approaches.

CONCLUSION

The large number of GRE sequences and acronyms can be made less confusing if one groups them into functional categories based on their general structure. This review provides a simplified nomenclature that is vendor-independent and adequately categorizes all GRE sequences commercially available on clinical MR imagers at the present time. I encourage MR vendors to adopt more uniform and descriptive terms for their GRE sequences of the future and, when given a choice, to select an accurate scientific designation for their sequence instead of an enigmatic acronym. ■

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