Imaging Acquisition & Reconstruction

Echo-Train Pulse Sequences: EPI, RARE & Beyond

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TARGET AUDIENCE
anyone interested in the signal behavior of echo-train sequences.

OUTCOME/OBJECTIVES
get a better understanding of inherent challenges and opportunites of the various echo-train sequences and to make an educated choice for a given application.

PURPOSE
to increase the efficiency of data acquisition. The problem addressed by echo-trains equences are the long waiting times in multishot sequences necessitated by signal recovery.

Nearly all of MR-imaging in use today is based on a k-space approach making use of the fact, that a linear spatial encoding field – i.e. a gradient – leads to a linear variation of the Larmor frequency of spins. Localization is then achieved by Fourier transformation of the acquired time domain signal into the frequency domain, which directly corresponds to the spatial domain. Consequently two-dimensional k-space data have to be acquired in order to form a two-dimensional image. The challenge for MR image formation thus is to find a way to cover the two-dimensional k-space with an intrinsically one-dimensional signal.

Over the history of MR quite a number of methods and strategies have been developed on how this goal is to be achieved. Conventional imaging sequences like spin echo imaging or gradient echo imaging acquire one line of k-space per excitation. Using non-rectilinear k-space trajectories like spirals all of k-space can be acquired after a single excitation. Echo-train sequences are those, which acquire k-space data piecewise – like conventional sequences – were parts of k-space are suitably encoded and acquired in multiple echoes after a single excitation of the spin system.

Due to this single shot acquisition mode echo-train sequences are inherently well suited for fast imaging since long waiting times necessary for recovery of magnetization are avoided. Acquiring all signals after a single echo-rain does, however, introduce other challenges associated to the signal evaluation of magnetization along the echo-rain.

The Fourier relationship between the image data and k-space data implies that all k-space points are acquired with equal weight. For echo-train pulse sequences this condition is clearly violated, since magnetization along the echo train decays with T2 and/or T2*, and the signal phase changes due to susceptibility or chemical shift effects – to name just a few of the main parameters acting on the echo-train signal.

Since each echo is typically acquired very fast under a readout gradient signal modulation in the readout direction is negligible.

The effective dwell-time (= time between acquisition of adjacent phase encoding points) is given by the echo spacing, which is rather large leading to appreciable signal modulation along the phase encoding direction of the image. Any signal modulation along the echo-train will act as a filter affecting the point-spread function of the image after transformation. Specific echo-train sequences will show different behavior due to the specific relevant parameters acting on the signal, but there are some general properties worthwhile to note.

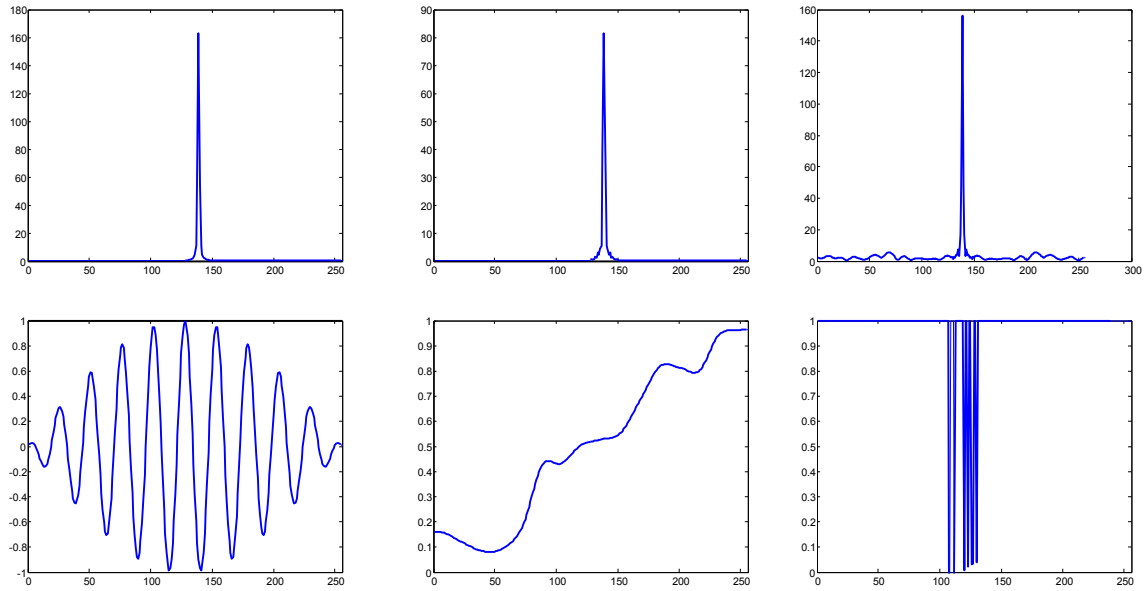

Fig.1 Effect of signal modulation: a) shows signal intensity from a single voxel with homogeneous spin density, d) the corresponding k-space signal. If d) is modulated with a continuous function, the corresponding signal (b) is only slightly broadened, whereas sudden variations (f) lead to artifacts across the full image width (c)

Following the inverse relationship between k-space domain and image domain it is apparent, that slow and monotonous changes in signal phase or amplitude will be rather benign leading to local effects, most typically broadening and/or shifting the signal (Fig.1 b,d), whereas a few ‘jerks’ during acquisition will spread out signal intensity all over the image and introduce severe artifacts (Fig.1 c,e).

In the following the most salient features of echo-train pulse sequences are discussed.

EPI

Echo planar imaging (EPI) has been introduced by Peter Mansfield in 1977 and is the ‘father’ of all echo-train sequences (1-3). Signal is acquired after a single excitation pulse by multiple reversals of the readout gradient to create one single long echo-train (Fig.2a). Phase encoding is introduced by using small ‘blips’ of the phase encoding gradient at each reversal of the readout gradient. Typically an initial pre-winding gradient is applied to bring the k-space trajectory to one corner of k-space (Fig.2b).

Optimization of the k-space trajectory requires two – in some respects – opposing challenges: High gradient amplitude will shorten the readout time for each echo, but requires short switching time (= high slew rate) for reversal of the readout gradient. Fig.3 demonstrates that for a given slew rate and image resolution there exists a minimum echo time as a function of

gradient amplitude. Higher gradient amplitude will lead to a disproportionate increase in switching time leading to reduced sampling efficiency and increase of total echo train length.

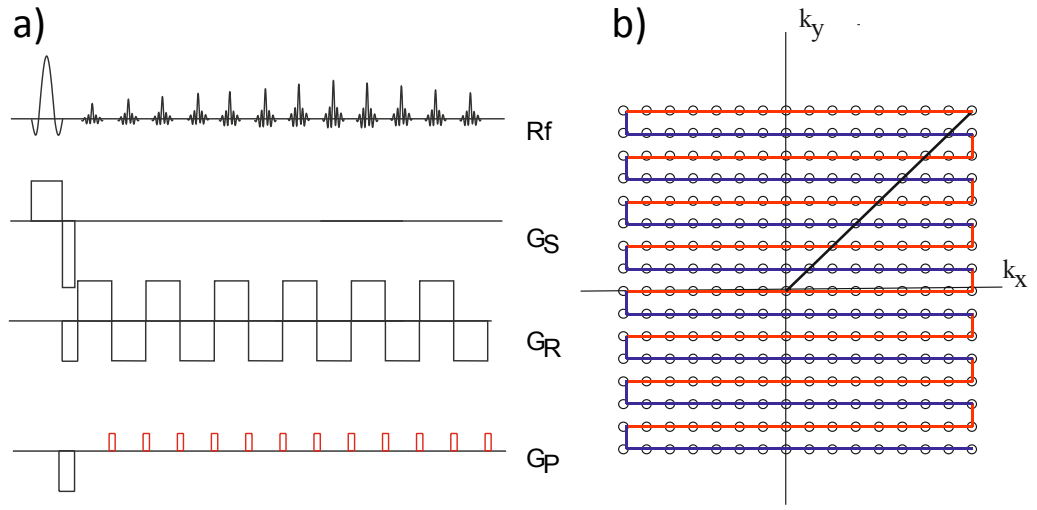

Fig.2 a) generic EPI-sequence, Rf denotes the excitation pulse and subsequent echo-train, GS, GR and GP the slice selection, readout and phase encoding gradient respectively, b) corresponding k-space trajectory.

Shortening of the echo train lengths is mainly achieved by increasing the slew rate. The maximum slew rate is for current scanners defined by physiological limits, therefore the total echo train length is more or less fixed. Indeed no major progress in shortening the echo train has been made over the last 25 years.

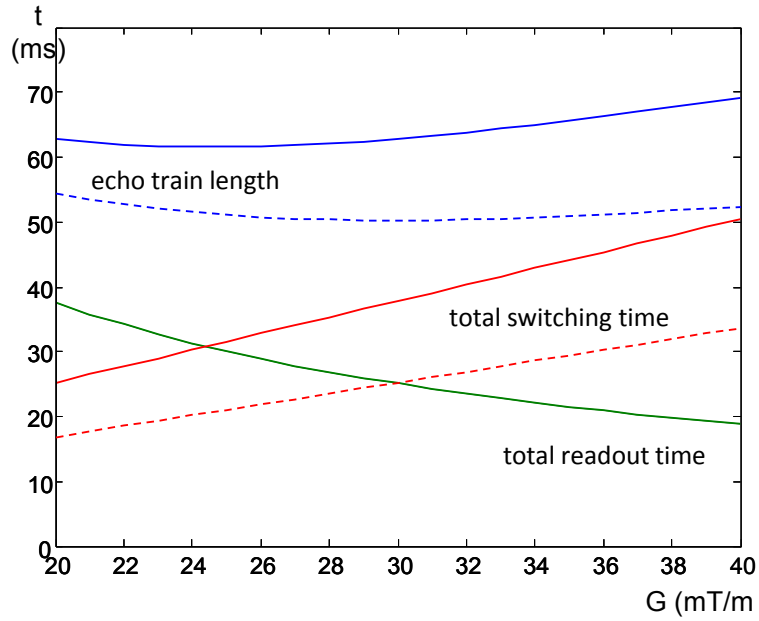

Fig.3 Total echo train length (b), switching time ® and readout time (g) of an EPI ech-train with 64 echoes and 2 mm spatial resolution as a function of gradient amplitude for slew rates of 100 T/m/s (full lines) and 150 T/m/s (dotted lines.

The main challenge in the practical realization of EPI lies in the realization of a ‘clean’ EPI-trajectory. Since any imperfections accumulate along the echo-train, even minor deviations can lead to severe artifacts. Most importantly eddy current effects will lead to deviations in the trajectory from its nominal form. Any continuous modulation of the signal along the data acquisition will affect odd and even k-lines in an opposite fashion due to the reversal of the

trajectory. Given basic Fourier theorem, alternating modulation of the signal will produce artifacts, which are displaced by half of the field of view in the phase encoding direction leading to the infamous 'Nyquist ghost'. Flyback-EPI avoids this artifact (4) by reading out data in alternating k-space lines only at the cost of considerable prolongation of the echo train length.

On current scanners the fidelity of the k-space trajectory has been considerably increased. residual imperfections can be perfected typically by using phase correction based on non-phase encoded signals acquired at each acquisition step and for each slice.

The main remaining challenge of EPI are artifacts caused by field inhomogeneities caused by local susceptibility effects introduced by the patients. These susceptibility effects lead to local changes in the resonance frequency as well as to local field gradients. Fig.4 shows typical susceptibility induced off-resonance effects and gradients of a human volunteer at 3T. Off-resonance frequencies will lead to a linear modulation of the signal phase along the encoding direction which – according to the shift theorem – translates to image distortions, which can be corrected for by appropriate means (5,6). Susceptibility induced gradients are superimposed to the imaging gradients. There effect depends on the gradient orientation:

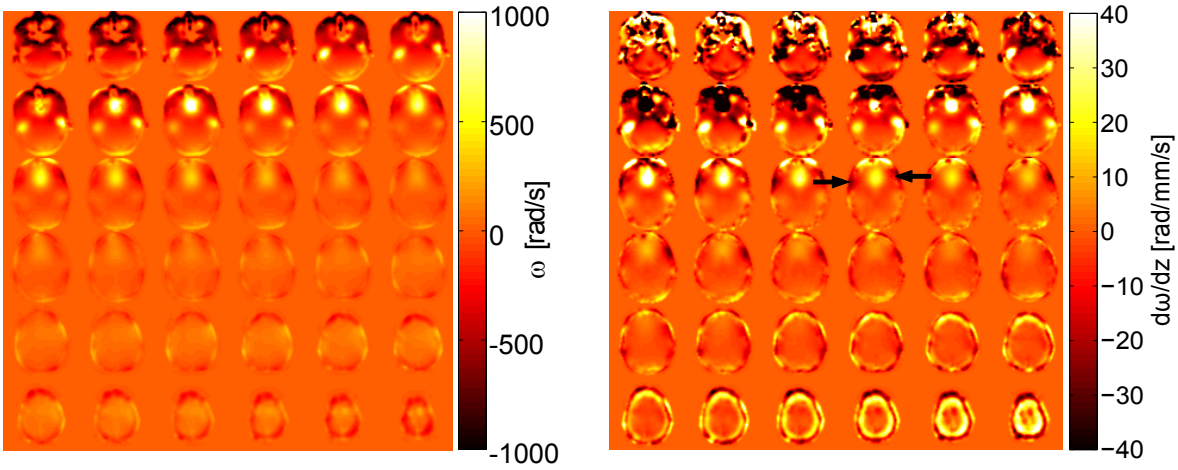

Fig.4 Off-resonance frequency map (a) and susceptibility gradient in z-direction (b) of the head of a normal volunteer at 3T. *(from Assländer Jet al, Neuroimage. 2013 , 59-70)*

- Susceptibility gradients along the slice selection gradient will lead to spin de-phasing across the slice and therefore to signal attenuation. This is the main source of the typical susceptibility voids observed i.e. in the frontal areas of the brain.

- Susceptibility gradients in the image plane are best understood using the concept of local k-space induced by Doug Noll (). A susceptibility induced gradient will lead to a shift in the k-space trajectory. As long as the shift is small, this will induce only a first order phase modulation in the image, which can be corrected for. If the shift exceeds half of the k-space width, signal nominally allocated to the k-space center will drop off the edge of k-space leading to irretrievable signal loss. As shown in Fig.4b such effects can be expected already at 3 T and pose severe problems at higher fields.

EPI and image acceleration

Parallel imaging using GRAPPE and/or SENSE are in routine use to accelerate standard imaging. For EPI the feasibility of parallel imaging techniques has been demonstrated (7,8), it is however used only with very moderate acceleration factors, if at all.. The main reason for this lies in the fact, that information about the signal phase is primarily used to correct for Nyquist ghost, the adding the creation of a kernel for GRAPPA reconstruction leads to reduced robustness of image reconstruction. A generic GRAPPA-acquisition scheme also requires a closer spacing of k-lines at the center of k-space compared to the k-space periphery in order to generate the reference lines, which may lead to additional eddy current problems. Acquiring the reference lines in a separate step poses challenges of temporal stability. Consequently in-plane acceleration is rarely used in EPI. Applying more advanced acceleration schemes like compressed sensing to EPI is even more challenging, since it requires a (pseudo-) random phase encoding scheme, which is hard to reconcile with EPI acquisition.

This is different for through-plane acceleration by use of multiband excitation with a CAIPIRINHA-reconstruction (9). This has been shown to work exceedingly well and is one of the hot topics in current development for EPI (10-12). Multiband-EPI does not accelerate acquisition of each single slice, but allows to dramatically reduce the total acquisition time for a multislice-experiment and therefore leads to very short repetition times in fMRI acquisitions.

RARE (TSE, FSE)

The creation of echo-trains by the formation of multiple spin-echoes has already been mentioned by Mansfield in one of his early EPI-papers, but practical realization took some time. This is mainly due to finding a proper way to apply phase encoding in a long train of spin echoes. An incremental phase encoding by gradient blips like in EPI will lead to a multitude off differently encoded spurious echoes created via stimulated echo pathways and thus to intractable image artifacts. The proper way to apply phase encoding is to use a phase encoding rewinding gradient after acquisition of the echo (13). This phase encoding rewinder brings the k-space trajectory back to the same position before each refocusing pulse. Consequently signal generated from different refocusing pathways will show identical phase encoding throughout the echo-train.

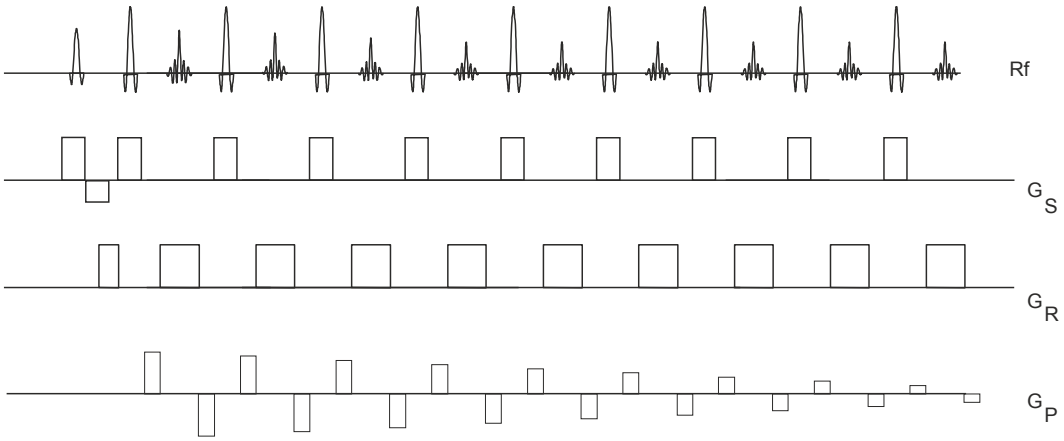

Fig.5a Generic scheme of RARE(TSE,FSE)-sequence. Labels as in Fig.2a

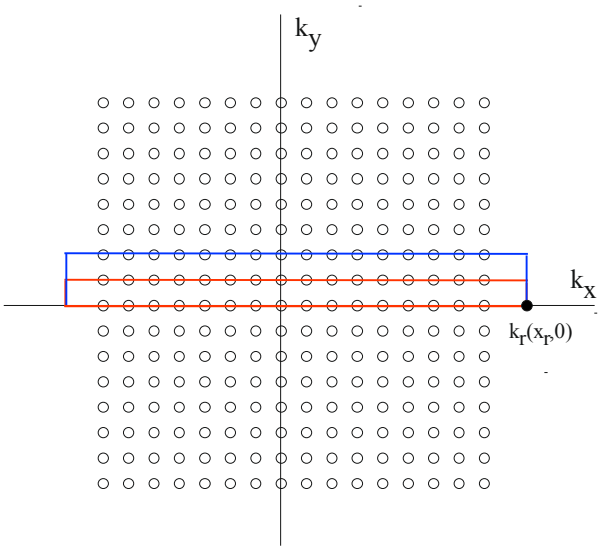

Fig.5b k-space trajectory in RARE (TSE, FSE). The phase encoding rewinder brings the k-space trajectory to the identical position prior to each refocusing pulse.

For phase encoding ordering two options exist: In a linear re-ordering scheme phase encoding is linearly increased between the minimum and the maximum phase encoding step. In centric reordering, phase encoding starts at some position in k-space and then hops alternatively and with increasing distance to one and the other side of the starting position. Both schemes ensure slow and continuous modulation of the signal across k-space and thus a very benign imaging behavior.

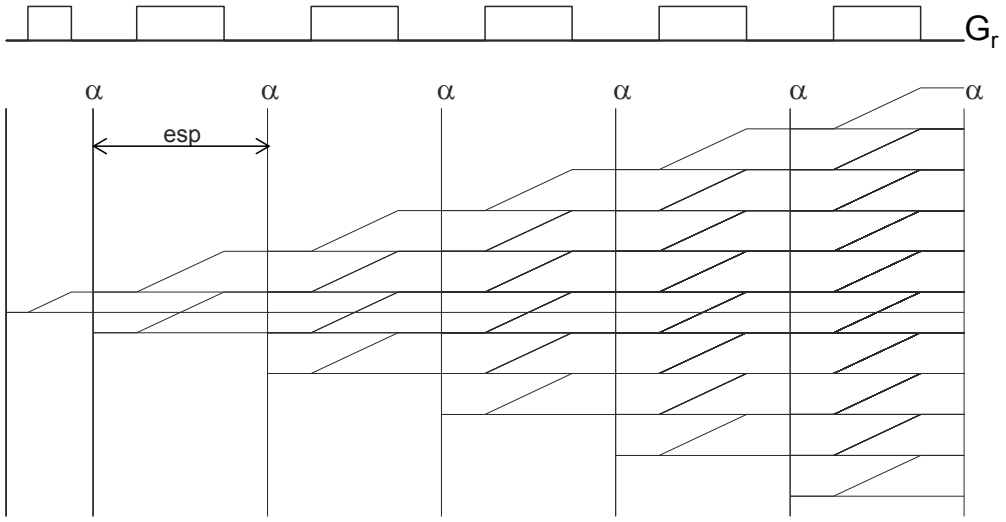

Fig.6 Extended phase graph of the RARE(TSE,FSE)-sequence with respect to the readout gradient Gr. At each refocusing pulse with flip angle α magnetization branches off into refocusing pathways of increasing order.

ehavior.

Due to the spin-echo mechanism the signal evaluation in RARE(TSE,FSE) will be dominated by T2. Off-resonance effects are refocused and can be ignored. Since image contrast is dominated by the signal intensity at the time of readout of the k-space center, images with different T2-contrast can be acquired using the same echo-train depending on the chosen phase encoding order. Due to the refocusing of field inhomogeneity effects, RARE (TSE,FSE) is also well suited for Half-Fourier reconstruction.

For refocusing flip angles lower than 180° signal will branch off into multiple refocusing pathways at each refocusing pulse (see Fig.6). The extended phase graph mechanism

allows an intuitive understanding and straightforward calculation of signal amplitudes for arbitrary refocusing flip angles (14). The constructive superposition of signals generated by the multitude of refocusing pathways leading to echo formation leads to unexpectedly high signal amplitude even at low refocusing flip angles (15,16). For low refocusing flip angles stimulated echo pathways will increasingly contribute to the measured signal. Since signal in stimulated echo pathways decays with T1 rather than T2, signal will become increasingly T1-waited. (17-19)

The very long echo-trains afforded by the use of low refocusing flip angles has been used for 3D-acquisition (20), where typically one (2D)-partition is acquired in each echo-train.

Since phase encoding for each echo starts from the same initial condition, RARE(TSE, FSE) is easily amenable to acceleration of parallel imaging encoding schemes including advanced concepts based on random phase encoding.

Compared to EPI data acquisition with RARE(TSE, FSE) is more robust but much slower. The necessity to apply one refocusing pulse for each acquired signal leads to much longer echo spacing of typically around 4-6 ms compared to 1 ms in EPI. Especially at high fields multiple refocusing pulses will also lead to severe limitations caused by physiological limits of power deposition (SAR). Nevertheless, echo acquisition based on low refocusing flip angles has been demonstrated even at 9.4 T.

GRASE

The GRASE-sequence uses a spin-echo acquisition scheme like RARE(TSE, FSE) but reading out multiple gradient echoes in each refocusing interval (21). It thus strives to combine the higher sampling efficiency of EPI with the robustness of RARE(TSE,FSE). Signals along the gradient echoes show signal evolution with T2* and are also subject to off-resonance effects, whereas signal evolution along the spin-echo train is governed by T2. Consequently the optimum implementation of GRASE is with 3D-acquisition, where the two different evolution mechanisms can be allocated to different phase encoding directions.

Summary

Although the basic principle of echo-train sequences is identical – i.e. to acquire all k-space signals after a single excitation pulse by formation of multiple echoes carrying different phase encoding, the mechanisms of signal formation via gradient reversal vice versa spin echo formation lead to vastly different imaging properties and consequently to very different areas of application. EPI is a workhorse sequence for fMRI and intensely used a fast readout module for a vast range of contract modulated sequences including diffusion imaging, diffusion tensor imaging, arterial spin labeling, dynamic susceptibility weighted (DWI)-imaging to name just a few. For standard diagnostic imaging EPI is hardly used due to inherent limits of spatial resolution and especially the complex signal behavior and liability to image artifacts especially outside the brain.

RARE(TSE,FSE) on the other hand is one of (if not the) main sequence for diagnostic imaging with very robust T2- and spin-density imaging. Even for T1-weighted imaging RARE(TSE, FSE) with shorter echo trains is increasingly used.

3D-Grase has been successfully applied to a number of applications like high-resolution fMRI of targeted regions or as a vehicle for arterial spin labeling.

Echo-train imaging is also well-suited to be combined with non-linear k-space trajectories like spirals. It remains a question of semantics, whether spiral EPI is still labeled as a echo-train sequence or whether a mulit-spin echo sequence with spiral readout is labeled as spiral RARE(TSE,FSE) or spiral GRASE. Intricacies introduced by non-linear sampling are covered elsewhere in this course.

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