Echo-Train Pulse Sequences: EPI, RARE & Beyond

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MR imaging is notoriously slow, in particular if only one echo or k-space line is acquired after each excitation in combination with long repetition times (TR). It was first proposed by Mansfield that much faster imaging is possible when more k-space information is encoded after a single excitation [1]. Echo planar imaging (EPI) traverses k-space in multiple gradient echoes, i.e. without radiofrequency pulse (RF) refocusing. Commonly, the occurrence of a gradient echo is defined as the time when the gradient moment between excitation and echo time (TE) is zero ($\int G\,dt = 0$). Multiple gradient echoes can be generated by repeated reversal of the readout gradient and the signal amplitude is determined by T2* decay. In EPI, these echoes are further phase encoded to cover k-space.

Mansfield already mentioned the possibility of an RF-refocused variant of EPI but it was Hennig who first showed that multiple spin echoes can be used to encode different k-space lines (RARE: rapid imaging with relaxation enhancement or TSE: turbo spin echo, or FSE: fast spin echo) [2]. In a spin echo the gradient echo condition has to be met by the spin echo timing condition. The time between excitation and refocusing has to be identical to the time between refocusing and the echo. If repeated refocusing pulses with equidistant echo-spacing are applied the so-called CPMG (Carr-Purcell-Meiboom-Gill) condition has to be met to ensure fully coherent superposition of all possible echo generation pathways. The signal intensity of the echo train is then determined by T2 decay only if ideal 180° refocusing pulses are applied. In imaging, often slice selective pulses or lower flip angle refocusing pulses are used. The echo signal intensity will then be determined by the contribution of higher order echo generation pathways, including stimulated echoes. The echo amplitudes can be calculated using the extended phase graph concept [3]. The echo amplitudes depend on the refocusing flip angle and even small variations of the flip angle can lead to significant variation in the signal intensity. “Intelligent” variation of the refocusing flip angles throughout the echo train can be employed to modulate the echo train signal intensity and control the RF power (SAR). These methods allow very long echo trains or significant SAR reduction (hyper-echoes) [4]. If the CPMG conditions are violated, i.e. if additional signal encoding is introduced after the excitation, not all echoes will interfere constructively but the echo train will split in two (even and odd) signal pathways. Images can still be generated if only signals from one pathway are acquired (FLARE) [5].

For Cartesian k-space encoding, each echo is phase encoded to fill a line in k-space and the sequence designer is generally free to assign the echoes to specific k-space lines, thereby determining properties of the imaging sequence. In EPI, however, the signal is decaying relatively quickly with T2* and thus delays due to the time required for large phase encoding moments between echoes should be avoided. As a consequence, only small phase encoding steps are encoded between echoes leading to a consecutive acquisition of neighboring k-space lines either in an up-down or down-up direction. In TSE, the phase encoding gradient moment has to be zero prior to every refocusing pulse. The sequence timing, i.e. the minimum echo spacing, is therefore determined by the maximum phase encoding gradient moment and the temporal order of phase encoding lines throughout the echo train is up to the sequence designer.

With respect to imaging properties and possible imaging artefacts two main aspects need to be considered in echo train imaging: 1) The signal variation along the echo train and 2) the distribution of echoes in k-space. In general and compared to an acquisition using single echoes with constant amplitude and phase, the consequences of signal variation between different echoes or k-space lines can be calculated as the undistorted image convolved with the Fourier Transform of the signal modulation along the phase encoding (echo train) direction. The image contrast, in particular the T2-weighting, is mainly determined by the echo time of the lines acquired with low phase encoding (center of k-space). In EPI this can only be varied by shifting the entire echo train, while in TSE, any echo can be sorted into the k-space center and thus the echo time can be between the first and last echo.

Amplitude variations along the phase encoding direction (that is once the echoes are sorted into k-space, not along the echo train) should generally be smooth. This is given for EPI echo trains that decay with T2* and are sorted consecutively into k-space. Smooth amplitude variations translate to broadening of the point spread function (PSF) and thus reduction of the effective resolution in phase encoding direction. The amount of smoothing in EPI depends on the ratio of echo train length and T2*. The larger flexibility in sorting TSE echoes into k-space as well as the potentially larger signal amplitude variation due to refocusing flip angle variation require more attention by the sequence designer. k-space signal jumps in the phase encoding direction and especially periodic modulations lead to discrete side lobes in the point spread function and thus replications of structure, such as object edges in the image in phase encoding direction. The freedom in echo sorting and flip angle variation may also allow to reduce signal amplitude variations in TSE echo trains and allow benign imaging properties with little blurring. In addition to the signal amplitude, the signal phase has to be considered. For spin echo based TSE under CPMG conditions the phase is identical in all echoes and therefore of little concern. The phase is mainly affected by system imperfections such as eddy currents. The echo phase is of much more importance and concern in EPI. Since the echoes are generate by gradient reversal along a free induction decay, many sources can affect the echo signal phase: 1) Any asymmetry of the echo, in particular a shift of the echo center vs. the acquisition window, will lead to an difference between even and odd echoes after reversal of every second line (due to gradient reversal between echoes). This leads to the so-called Nyquist or N/2-ghost and many methods have been proposed to correct for this artefact in the reconstruction. 2) A deviation of the local Larmor frequency from the system frequency leads to a constant phase increment along the phase encoding direction in k-space and therefore to a local shift of this position in the image. Consequently, magnetic field inhomogeneities throughout the object - mainly caused by susceptibility differences between different tissue types - result in geometric distortions. Correction methods can be based on reference measurements of the magnetic field distribution, mapping of the local shift in the PSF or measurements with opposing phase encoding directions.

Acceleration of standard imaging methods commonly results in a loss of SNR proportional to the square root of the acceleration factor times the g-factor. In echo train sequences, the shortening of the echo train length and potential reduction of TE can lead to an even increase SNR, an effect that was first reported for diffusion weighted EPI.

References:

1. Mansfield, P. and A.A. Maudsley, *Planar spin imaging by NMR.* J. Magn. Reson., 1977. **27**: p. 101-119.
2. Hennig, J., H. Nauerth, and H. Friedburg, *RARE imaging: a fast imaging method mfor clinical MR.* Magnetic Resonance in Medicine, 1988. **3**: p. 823-833.
3. Hennig, J., Echoes - How to generate, recognize, use and avoid them in MR-imaging sequences. Part I+II. Concepts in Magnetic Resonance, 1991. 3: p. 125 - 143 and 179 - 192.
4. Hennig, J., M. Weigel, and K. Scheffler, *Multiecho sequences with variable refocusing flip angles: optimization of signal behavior using smooth transitions between pseudo steady states (TRAPS).* Magn Reson Med, 2003. **49**(3): p. 527-35.
5. Norris, D.G., *Ultrafast low-angle RARE: U-FLARE.* Magn Reson Med, 1991. **17**(2): p. 539-42.