Spoiled & Balanced Gradient-Echo Sequences

Klaus Scheffler
Max Planck Institute Tübingen, Germany
University of Tübingen, Germany

1 Introduction

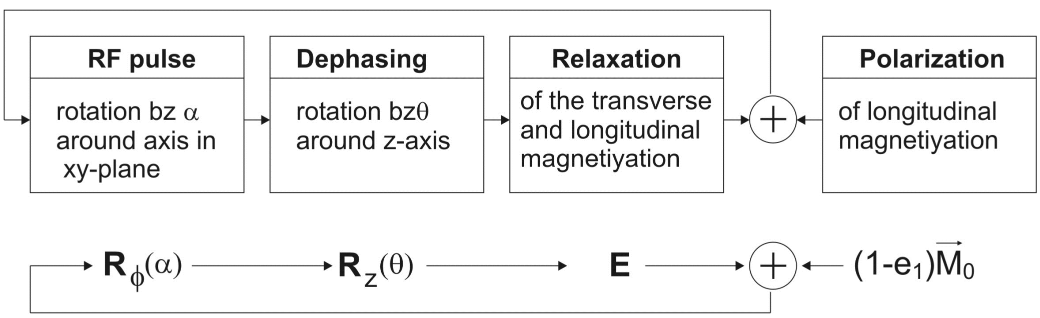
Rapid imaging sequences are characterized by a fast train of excitation and gradient pulses. Between excitation pulses or within TR, the magnetization is not able to return to its thermal equilibrium. As a consequence, excitation pulses will influence both the remaining transversal and the remaining longitudinal magnetization. The steady-state magnetization of a multi pulse experiment is thus a mixture or superposition of different transversal and longitudinal states, and the acquired image amplitude becomes a complex function of the investigated tissue's relaxation properties.

The Steady state free precession

The steady state of the magnetization will be established after some excitation and gradient pulses. The steady state is characterized by a certain distribution of magnetization vectors within the spatial 3D space. If a steady state has been established this distribution will be exactly the same for each TR. It is obvious that a steady state can only be reached for sequences with a

1. fixed TR (in order to have identical T1 and T2 relaxation within each TR period)
2. constant flip angle (the phase of the excitation pulse may vary linearly or quadratically from pulse to pulse)
3. constant dephasing within TR (the dephasing induced by switched gradients and susceptibility effects at a certain spatial position must be the same within each TR) [1,2]

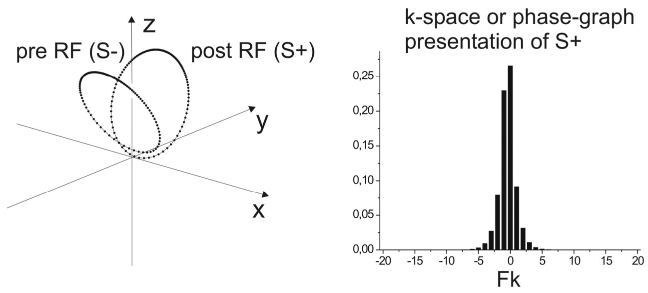
From item 3 it can be deduced that the phase encoding gradient, which changes from excitation to excitation has to be refocused (compensated by a second gradient pulse with opposite gradient area). Sequences with non-refocused phase encode gradients do not establish a steady state and additionally produce image artifacts. The analytical description of the steady state in the spatial domain can be achieved by solving the eigenvector equation that describes the three processes of excitation (rotation by α around an axis in the x-y plane), dephasing (rotation by θ around z-axis) and T1 and T2 relaxation:



Mathematically this corresponds to:

$$\vec{M}^+ = \mathbf{R}_x(\alpha)\left(\mathbf{R}_z(\phi)\mathbf{E}\vec{M}^+ + M_0(1-E_1)\hat{z}\right) \tag{1}$$

The (unique) solution in the spatial domain and in the k-space is shown below for some fixed parameters of TR, a, T1, and T2.

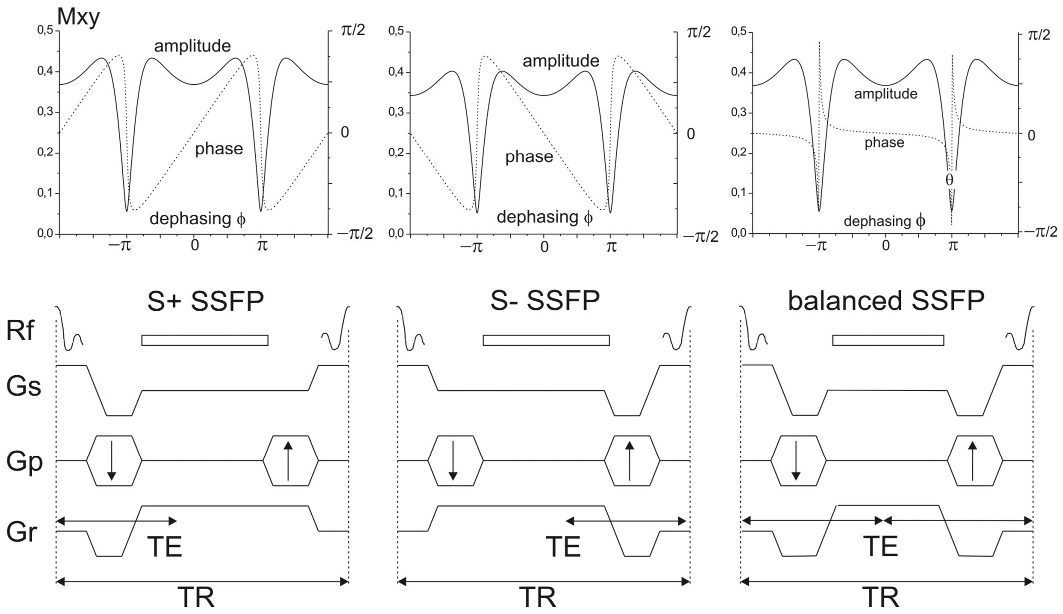


The corresponding analytical solution is given by [3]

$$\vec{M}^+ = \left(\mathbf{1} - \mathbf{R}_x(\alpha)\mathbf{R}_z(\phi)\mathbf{E}\right)^{-1} M_0(1-E_1)\hat{z} \tag{2}$$

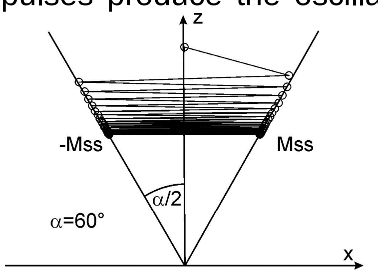
The steady state magnetization does not depend on the chosen gradient waveform that is switched between the excitation pulses. The steady state magnetization generated just before and after the excitation pulse (sometimes called S+ and S-, respectively) is thus identical for all types of gradient echo sequences that are periodic within one TR.

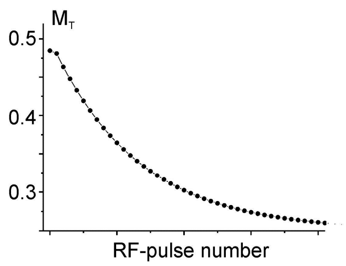
The type of the read-out gradient selects whether the S+ or the S- magnetization (or both) is used for imaging. A conventional bipolar read-out gradient selects the S+ signal (refocused FLASH, GRASS, FAST, sometimes FISP, FFE, …), whereas the time reversed gradient waveform selects the S- signal (PSIF, CE-FAST, CE-FFE, …). The resulting signal intensity of these sequences can be calculated by summing up the magnetization given in Eq. 2 over a full 2π period (if the gradient induced dephasing between excitation pulses is adjusted in such a way that the phase difference within one imaging voxel is ±π) [4,5].



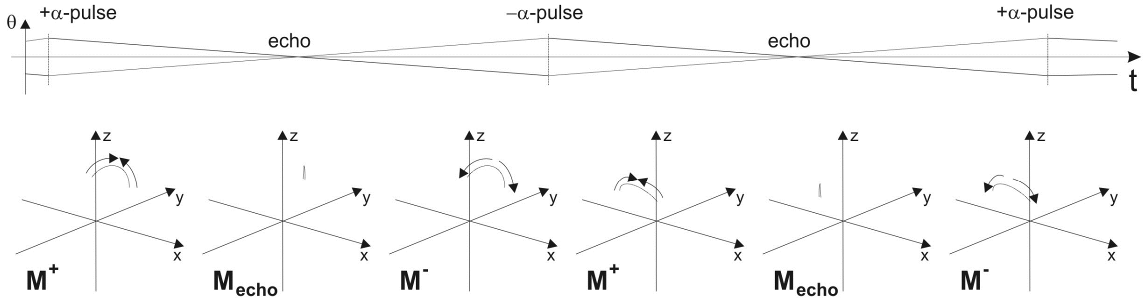
Balanced steady state free precession

For balanced SSFP the gradient induced dephasing between excitation pulses is zero, which means that each gradient lobes are fully refocused or balanced. The balanced SSFP excitation train consists of an initial $\alpha/2$ preparation pulse followed by a train of alternating $\pm\alpha$ excitation pulses [6]. The $\pm\alpha$ pulses are separated by TR whereas the time interval between the $\alpha/2$ preparation pulse and the first $-\alpha$ pulse is TR/2. Since switched gradient pulses between consecutive excitation pulses have no influence on the magnetization it is very easy to analyse the motion of the magnetization during such an excitation pulse train. The initial $\alpha/2$ pulse brings the magnetization towards its steady state position, and subsequent alternating $\pm\alpha$ pulses produce the oscillation around the z-axis. T1 and T2 relaxation produces a certain damping of the magnetization. All magnetization vectors are aligned on a $\alpha/2$ cone and the amplitude of their transverse part converges towards the steady sate, resulting in a smooth decay of the transverse magnetization.





The eigenvector equation (1 and 2) can also be used to describe SSFP sequences for which the gradient induced dephasing between excitation pulses is zero. In contrast to non-balanced SSFP the motion of the magnetization between excitation pulses can be visualized very nicely for balanced SSFP. Due to the fact that balanced SSFP shows practically no dephasing within TR the resulting magnetization is just a single vector (totally coherent, not a sum of dephased configurations). Using alternating excitation pulses the magnetization flips continuously between two positions that are located on a $\alpha/2$ one.



From this figure it can also be seen that it is advantageous to start the balanced SSFP excitation train with an initial $\alpha/2$ preparation, which brings the magnetization very close to the steady state.

4 References

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