Calculation of predefined echo amplitudes for TFE sequences

A. N. Priest[1], P. M. Bansmann[1], G. Adam[1]

[1]Department of Diagnostic and Interventional Radiology, University Hospital Hamburg-Eppendorf, Hamburg, Germany

Introduction

Turbo-field echo (TFE) sequences (or k-space segmented FAST/FISP/GRASS) can be used for many applications, including coronary artery vessel wall or lumen imaging (with ~10 pulses per segment). These sequences are often used with centric phase-encode ordering to allow the use of preparation pulses. They offer significantly higher signal-to-noise ratios (SNR) than RF-spoiled sequences and may have advantages at high fields due to their low sensitivity to off-resonance effects. The SNR is determined by the first echo amplitude and the resolution by the variations in amplitude throughout the echo-train. However, substantial amplitude variations can occur within the first few echoes, with oscillatory behaviour even for moderate flip angles, leading to a poor point-spread function (PSF) and thus to reduced resolution (blurring). For practical applications, an acceptable compromise must be found between resolution and SNR.

The evolution of echo amplitudes can be controlled, reducing signal oscillations, by varying the flip angle during the pulse train [1]. We propose a simple method to calculate a series of flip angles to achieve a pre-defined sequence of echo amplitudes, allowing improvements in either SNR or resolution. This method uses the extended phase-graph (EPG) algorithm [2] which has been used to model gradient-echo sequences using a constant flip angle [3]. The EPG method has recently been used to achieve arbitrary predefined echo amplitudes for fast spin echo sequences [4] by sweeping the flip angle. We now use this method to produce a predefined series of echo amplitudes for short TFE sequences. Its elegance lies in the fact that, for a given phase-state configuration, the next required flip angle can be calculated using a simple analytical expression; numerical optimisation methods are not needed.

Theory

In the EPG formalism, the magnetisation is expressed in terms of a phase state configuration containing states F_k and Z_k for integer k. As described in ref [4], an RF pulse α_n transforms F_k and Z_k coherences to F_k^+ and Z_k^+ according to:

$$\begin{pmatrix}F_k\\F_{-k}\\Z_k\end{pmatrix}^+ = T(k,\alpha_n)\begin{pmatrix}F_k\\F_{-k}\\Z_k\end{pmatrix}$$

where the matrix T is given by

$$T(k,\alpha_n)=\begin{pmatrix}\cos^2\frac{\alpha_n}{2} & -\sin^2\frac{\alpha_n}{2} & \sin\alpha_n\\ -\sin^2\frac{\alpha_n}{2} & \cos^2\frac{\alpha_n}{2} & \sin\alpha_n \\ -\frac{1}{2}\sin\alpha_n & -\frac{1}{2}\sin\alpha_n & \cos\alpha_n\end{pmatrix}$$

following ref [3] with $\phi = 90°$; this approach gives only real values for all states and correctly handles the F_0 coherence.

Following this the phase states before the next pulse are given by:

$$F_{k+1} = E_2 F_k^+ \text{ and } Z_k = E_1 Z_k^+ \text{ for } k \neq 0,\ Z_0 = E_1 Z_0 + 1 - E_1, \text{ with } E_{1,2} = \exp(-TR/T_{1,2})$$

The initial conditions are $Z_0 = 1$ and all other states = 0. These expressions allow the echo signals (proportional to F_0) to be calculated for any series of flip angles, and also to derive the next flip angle α_n that produces a desired echo amplitude I_n, according to:

$$\tan\left(\frac{\alpha_n}{2}\right) = \frac{Z_0 \pm \sqrt{Z_0^2 + F_0^2 - I_n^2}}{I_n + F_0}$$

The desired amplitude can therefore be achieved only if $I_n^2 < Z_0^2 + F_0^2$.

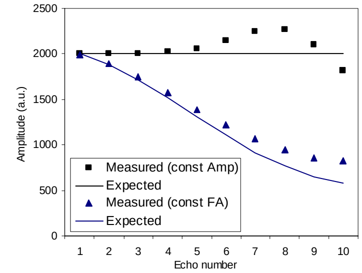

Fig. 1: Measured (symbols) and expected (lines) data for constant flip angle of 20° and constant echo amplitude

Methods

Flip angle series were calculated for 10 pulses, using TR = 8 ms and T_1/T_2 = 450/380 ms. Of two possible solutions at each stage, the lower flip angle was always chosen. The desired echo amplitudes were compared with measured values obtained from a phantom by switching off the phase-encode gradients. TFE images of a resolution phantom were acquired using both a constant flip angle and the calculated flip-angle sweeps. A 3T Intera system was used (Philips Medical Systems, Best, The Netherlands). A measurement of the actual flip angle was performed [5] to avoid global flip angle miscalibrations.

In addition to constant amplitude echo-trains, flip-angle sweeps were implemented for decaying exponentials (decaying by factors of 2, 3 and 4 over 10 echoes) and for Gaussian decay (by factors of 3, 4 and 6 over 10 echoes). The decaying profiles permitted the use of higher initial flip angles than the constant amplitude approach (up to ~35° for exponential decays, ~30° for Gaussian and ~25° for constant amplitude). Profiles though the resolution phantom images were measured for object sizes/spacings of approximately 1/1 and 2/2 pixels, and normalized to the signal in a uniform region of the phantom.

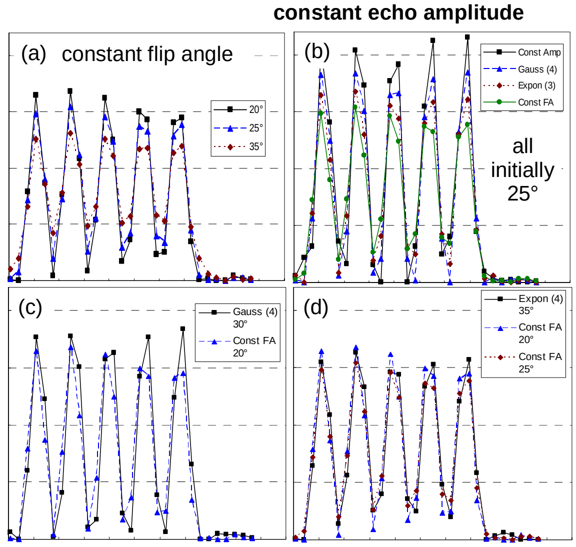

Figure 2: Profiles (amplitude vs position) through resolution phantom with sizes/spacings ~2 pixels: (a) constant flip angles; (b) different methods all for 25° initial angles; comparisons of constant angle with (c) Gaussian and (d) exponential decays. (decay factors over echo train given in brackets).

Results

Fig. 1 shows measured and theoretical echo amplitudes for constant flip angle and an example with constant echo amplitude. Fig. 2 shows measured profiles through a resolution phantom. The resolution deteriorated as the (constant) flip angle was increased. For every flip angle, all the calculated sweeps gave superior measured resolution profiles (objects 2/2 pixels) in comparison with the corresponding constant flip-angle images. Additionally, all Gaussian sweeps starting from 30° gave slightly better resolution profiles even than 20° constant flip angles; and exponential sweeps starting from 35° gave resolution profiles better than 25° constant flip angle and of comparable quality to 20° constant flip angle images. For the smallest objects (sizes 1/1 pixels) most profiles were relatively poor, but the constant-echo-amplitude sweeps showed improved resolution (Fig. 3).

Discussion and Conclusions

The calculated flip angle sweeps, giving constant amplitude, decaying exponential and Gaussian echo amplitudes, all reduced signal oscillations and controlled the signal decay, leading to improved resolution compared to constant flip angle approaches. Alternatively, using exponential or Gaussian sweeps, substantially higher initial echo amplitudes (and thus higher SNR) could be achieved than with constant flip angle approaches without compromising resolution. This approach can also be simply applied to calculate flip angle sweeps for different initial conditions, for example following magnetisation preparation pulses. It could also be used to search for a rapid approach to the pseudo-static steady state for TFE sequences.

The discrepancy between the measured and theoretical echo amplitudes can be attributed to an inadequacy in our measurement, namely flip-angle inhomogeneities within the phantom, and subsequent averaging over non-uniform signals. Future measurements will image the local echo amplitude, which should correct this problem.

This method can be applied for example to high-field coronary artery imaging of either lumen or vessel wall, and should help to achieve improved resolution and/or SNR compared to constant flip-angle approaches.

The use of flip angle sweeps leads to an increased power deposition (SAR) which may be a restriction for rapidly repeated sequences. However coronary imaging with TFE is typically well below this limit and should not be adversely affected.

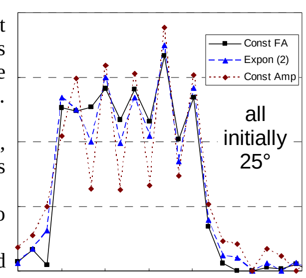

Figure 3: Profiles through phantom with sizes/spacings ~1 pixel.

Acknowledgement

We thank the Florindon Foundation, Switzerland for funding.

References

[1] Mugler JP et al, Magn Reson Med 1992; 28:165-185.
[2] Hennig J. J Magn Reson 1988;78:397-407.
[3] Scheffler K. Conc Magn Reson 1999;11:291-304.
[4] Henning J et al. Magn Reson Med 2004;51:68-80.
[5] Stollberger R et al. Magn Reson Med. 1996;35:246-51.