Tailored shaping and time resampling functions for inversion pulses at 7T

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Introduction:

The RF transmit field is severely inhomogeneous at ultrahigh field, due to both RF penetration and RF coil design issues. This particularly impairs image quality for sequences that use inversion pulses such as MPRAGE, and limits the use of quantitative ASL sequences such as FAIR. A number of approaches to solving this problem have been proposed, often requiring additional hardware. Here we have taken a simpler approach using a search algorithm to produce inversion pulses tailored to take account of the heterogeneity of the RF transmit field at 7T. The goal was to create a slice selective inversion pulse which worked well (good slice profile and uniform inversion) over the range of RF amplitudes typically obtained, whilst still maintaining an experimentally achievable pulse length and pulse amplitude in the brain at 7T. The pulses used were based on the FOCI (Frequency Offset Correction Inversion) technique (Ordidge, 1996) as well as time dilation of functions (Conolly, 1991; Shen 2004), but the RF amplitude, frequency sweep and gradient functions were all optimised using a Genetic Algorithm using an evaluation function that took account of both the desired inversion profile and the transmit field inhomogeneity.

Theory:

The pulse is described by the following equations:

$(a) B_1(t) = A(t)\mathrm{sech}(\beta T(t))$ (b) $\Delta\omega(t) = -A(t)\mu\beta\tanh(\beta T(t))$ (c) $G(t) = A(t)$

Where the time resampling function $T(t) = (\tau_1 t^5 + \tau_2 t^3 + t)/(\tau_1 + \tau_2 + 1)$, changes the sampling of the tanh/sech functions from uniform intervals to variable intervals ($t \in [-1,1]$). This polynomial was chosen as it was monotonically increasing, reasonably general and yet described by a limited number of search parameters. This method maintains symmetry of 'time' about zero as well as the starting and end points.

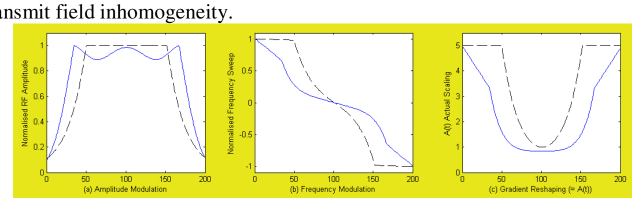

Fig 1: (a) AM, (b) FM and (c) Gradient shapes for FOCI (- - -) and GMTR-FOCI Inversion Pulse(–)

Methods:

For the C-Shape FOCI pulse, *A(t)* was defined to consist of two distinct segments, a linear segment and a curved segment (fig 1c), where the width of the line segment is coupled to the maximum *A(t)*. Here we have taken a more general approach to allow a bigger space to be searched. Hence the linear segment is not constrained to be horizontal, and its shape is determined by the variables G_{max}, the maximum value of $A(t)$, w, the width of the line segment (independent of G_{max}) and r_1, related to the slope of the line segment. The curved segment is a polynomial, $b(1)t^2 + b(2)t^4 + b(3)t^6 + b(4)t^8 + G_{min}$. ($t \in [-1,1]$) and is determined by r_2, r_3, r_4, r_5 in a manner which guarantees continuity between line and curved segments.

To determine the optimum pulse shape a genetic algorithm was used, which used a Bloch simulation of the effects of the RF pulse on the magnetisation. We defined weighted inversion profile accuracy (WIPA) function as the evaluation function which measured the performance of the pulse, and which was designed to take account of both the accuracy of the inversion profile and its sensitivity to RF amplitude. We first defined an inversion profile accuracy (IPA) function as 1000 (arbitrarily chosen) divided by the sum of the square differences between an ideal inversion profile and the simulated inversion profile. IPA was then calculated for three RF levels typical of the RF field at 7T (L1, L2, L3=3, 5, 7 μT) and the WIPA calculation was biased in favour of the lower RF amplitude thus:

$$WIPA(L_1, L_2, L_3) = IPA(L_1)\frac{L_3}{L_1 + L_2 + L_3} + IPA(L_2)\frac{L_2}{L_1 + L_2 + L_3} + IPA(L_3)\frac{L_1}{L_1 + L_2 + L_3}$$

A Genetic Algorithm was used to find an inversion pulse such that WIPA was at/near maximum. We evaluated a number of vectors ($V = [G_{max}\ w\ r_1\ r_2\ r_3\ r_4\ r_5\ \mu\ \beta\ \tau_1\ \tau_2]$) which determine $A(t)$ and $T(t)$ and hence $B_1(t)$, $\Delta\omega(t)$ and $G(t)$. Firstly 5000 random vectors were evaluated. Taking the 'best' 350 vectors, two-point crossover and mutation was applied over 75 generations which was when no improvement was seen in the previous ten generations. The 10 best solutions were evaluated between 2 and 10μT to determine a 'winner'. This winner was then subjected to a process known as greedy hill climbing to improve marginally on its performance.

Evaluation:

FOCI, Hyperbolic secant and GMTR-FOCI (Genetically Modified Time Resampled FOCI) were used to invert a 40 mm slice perpendicular to the imaging plane of an EPI scan. Data were acquired on a 7T Philips Achieva scanner with a 16 channel Nova Medical brain receive coil, and using a saline solution spherical phantom. Data were acquired at a variety of Inversion Times (TI), and the resulting images were fitted to $S=So(1-Ae^{-TI/T1})$ for So, T1 and A. Maps of A show the inversion efficiency across the slice profile. This was carried out not only for the standard B1 amplitude used for the FOCI pulses, but also for a range of lower amplitudes to simulate the effects of RF heterogeneity. We also used the GMTR-FOCI pulse when acquiring whole head brain MPRAGE scans.

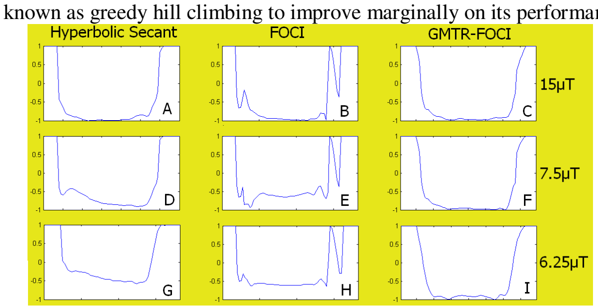

Fig 2 : Inversion Profiles for HSC, FOCI and GMTR-FOCI @ 100%, 50% and 41.67% of Maximum RF amplitude.

Results:

The GMTR-FOCI waveforms are shown in figure 1. The Bloch simulation showed that the GMTR-FOCI could produce an inversion with a similar profile to the FOCI pulse at for the same pulse amplitude and pulse length (fig 1), but (in contrast to the FOCI pulse) this performance was maintained as the RF amplitude dropped. Figure 2 shows that this pulse gave a good slice profile experimentally, with narrow pass bands, and low sensitivity to reduced B1 amplitude. It is interesting to note that experimentally the inversion profiles for the FOCI pulse (B,E,H in Fig 2) are distorted in at the edge of the profile. It is likely that this is due to errors in reproducing the gradient reshaping curve (shown in Fig 1). The GMTR-FOCI pulse gradient reshaping function is smoother and probably less sensitive to any non idealities in the gradient system (C,F,I in Fig 2).

Figure 3 shows that the FOCI pulse led to loss of GM/WM/ contrast particularly in the temporal lobes which was recovered when using the GMTR-FOCI pulse (although the SNR was still low, due to low RF reception at that position.)

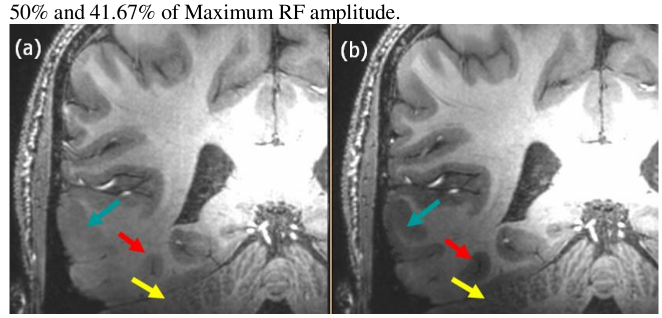

Fig 3 : Coronal Brain scan using (a) FOCI, (b) GMTR-FOCI

Discussion:

A GA has been used to design a slice selective inversion pulse that can perform well across the range of B1 amplitudes currently achievable in the human brain at 7T using conventional hardware. It is likely that the smooth gradient waveform used by this pulse also contributes to making it robust to experimental conditions, though this is now investigated with further experiments. **References:** Ordidge, RJ et al. MRM 1996:36: 562-566 (1996), Silver et al. Phys. Rev A. 31:2753-2755 (1985) , Connolly, S. et al, MRM 18, 28-38(1991) **,** Shen et al. JMRI 20, 531-537 (2004). **Special Thanks:** SPMMRC and fp6 Marie Curie Actions.