B1 insensitive genetically altered refocusing pulses for ultrahigh field spin echo imaging

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B1 inhomogeneity at ultrahigh field limits the use of spin echo pulses. In the past adiabatic refocusing pulses have been proposed to provide B1 insensitivity but are generally rather long for imaging applications. Urgurbil et al. [1] proposed the use of a Numerically Optimised Modulation (NOM) scheme to improve the adiabaticity over the whole length of a BIR4 pulse and this method provides better performance for shorter pulses. NOM resamples the AM and FM functions with reference to the adiabatic condition and is restricted to looking at on-resonance effects. Following from this work, we attempted to optimize the resampling function via a Genetic Algorithm. The evaluation function considers B1 and B0 inhomogeneities to tailor the optimization to 7T conditions, requiring the study of off-resonance behaviour. The evaluation considered spectral profiles (from -150Hz to 150Hz off resonance), across a range of maximum RF amplitude, generated using a Bloch Equation Simulator. The length of the pulse became a variable, constrained to allow practical implementation of the pulses.

Methods

Re parameterize the BIR4 pulse: Below are the equations for B1 independent genetically altered refocusing (BIGAR) pulses based on the BIR4 equations:

$$AM(t) = B_1 \tanh(\beta\tau((1-4t)/T))); \quad (0 \le t \le T/4);$$
$$B_1 \tanh(\beta\tau((4t)/T-1))); \quad (T/4 \le t \le T/2)$$
$$B_1 \tanh(\beta\tau((3-4t/T))); \quad (T/4 \le t \le 3T/4);$$
$$B_1 \tanh(\beta\tau((4t/T-3))); \quad (3T/4 \le t \le T)$$

$$FM(t) = -\mu \sec h(\beta\tau((1-4t/T))); \quad (0 \le t \le T/4);$$
$$\mu \sec h(\beta\tau((4t/T-1))); \quad (T/4 \le t \le T/2);$$
$$-\mu \sec h(\beta\tau((3-4t/T))); \quad (T/4 \le t \le 3T/4);$$
$$\mu \sec h(\beta\tau((4t/T-3))); \quad (3T/4 \le t \le T);$$

In these equations

$$\tau(\kappa) = \frac{\sum_{k=1}^{10} \tau_k \kappa^k}{\max(\sum_{k=1}^{10} \tau_k \kappa^k)}$$

where $\kappa \in [0,1], \tau_k \in [-1,1], t \in [0,T]$ and $\tau(\kappa)$ is the coefficient of β (e.g. $\tau(1-4\tau(t)/T)$ when $(0 \le t \le T/4)$).

Our input vector into a genetic algorithm is $[\beta\, T\, \mu\, \tau_1 \tau_2 \tau_3 \tau_4 \tau_5 \tau_6 \tau_7 \tau_8 \tau_9 \tau_{10}]$. We sought values for these 13 parameters which generate BIGAR pulses.

Evaluate New Pulse: We use a Bloch Equation Simulator to generate magnetisation MY and MX resulting from the pulse acting on magnetization in an initial state MY = 1, MX = 0, MZ = 0. Resultant longitudinal magnetisation is not considered. The ideal response would be MY=-1, MX=0, so we calculate the error as

$$e(pulse, B_1) = abs(-1 - MY) + abs(MX)$$

Refocusing behaviour was evaluated over a 300Hz of bandwidth, chosen as the normal range of B0 inhomogeneity found in field maps of the brain at 7T. Both the MX and MY profiles considered 30 equally spaced points, so that the maximum error e is 90. To use the genetic algorithm to reduce sensitivity to B1 variations we evaluated the pulse refocusing performance at B1 of 7, 8.75, 10.5, 12.25 and 14 μT (the maximum allowable RF amplitude on the Philips scanner and Nova coil at 7T is 15 μT). Our evaluation function was thus

$$V(pulse) = 450 - e(pulse,7) - e(pulse,8.75) - e(pulse,10.5) - e(pulse,12.25) - e(pulse,14); \quad 0 \le V(pulse) \le 450$$

We compared the results to refocusing pulses typically used on the scanner (Optimum Echo 2 and Truncated Sinc Pulses). The Optimum Echo 2 pulse performed considerably better than the sinc pulse (but worse than the BIGAR Pulses).and therefore only Optimum Echo 2 results are shown for comparison here. Brain Images were obtained using a Spin Echo EPI sequence using a BIGAR refocusing pulses of 15ms, 9.3ms or 6.4ms or the Optimum Echo 2 Pulse. The excitation was a standard sinc pulse and therefore also showed sensitivity to B1, particularly at points far from the centre of the RF coil. Therefore to evaluate the experimental performance of the pulse the following function was calculated $C(j,k) = \frac{I_1(j,k) - I_2(j,k)}{I_1(j,k) + I_2(j,k)}$ where I_1 is an image generated using a BIGAR ulse and I_2 using an Optimum Echo 2 pulse. C(j,k) is a normalized measure of the relative abilities of the pulses to retain the transverse magnetization. C(j,k) > 0 indicates the BIGAR produces larger intensity at the point (j,k) where as C(j,k) < 0 indicates that Optimum Echo 2 produces higher intensity at the point (j,k).

The Genetic Algorithm was used to produce BIGAR pulses for pulse lengths constrained to 15, 10 and 7ms (the different pulses are not time stretched/contracted versions of each other). Separate Dynamic Genetic Algorithms were executed, each using Tournament Selection, Crossover Method Switching, Mutation and Permutation Hill Climbing.

Fig 1 shows simulation results indicating the robustness of the shortest of the BIGAR pulses to B1 variation (longer pulses performed even better). Fig 2 shows that in practical use BIGAR pulses achieve higher intensity at the periphery of the brain (in the presence of B1 inhomogeneity). Fig 3 shows maps and histograms of C(j,k) and demonstrates that at the level of red nuclei where B1 errors are particularly significant, BIGAR pulses can achieve better refocusing (higher signal - C generally >0).

Discussion

We have developed non selective refocusing pulses with reduced sensitivity to variation in B1 amplitude for use at 7T. Future work will be focused on using this pulse in 3D spin echo sequences such as GRASE.

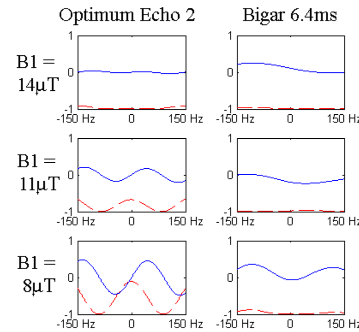

Fig 1: Comparison of simulated transverse magnetization profiles, MY - , MX __

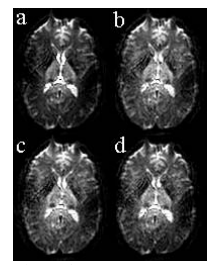

Fig 2: Spin Echo EPI Images using (a) Optimum Echo 2 and BIGAR Pu1ses of length (b) 15ms, (c) 9.3ms, (d) 6.4 ms

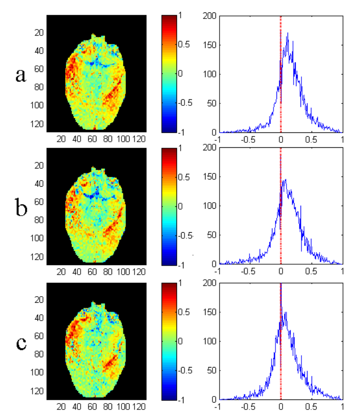

Fig 3: C(j,k) Maps at the level of red nuclei with their histograms. BIGAR Pulses, I_1 in (a) 15ms, (b) 9.3ms and (c) 6.4ms. Optimum Echo 2 is I_2 in (a),(b) and (c).

References

[1] Ugurbil, K., Garwood, M. and Rath, A. R. (1988) Optimization of modulation functions to improve insensitivity of adiabatic pulses to variations in B1 magnitude. J. Magn. Reson. 80:448-469.

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