Design of slice multiplexed pulses for simultaneous multislice imaging

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Introduction: Recently we introduced a new method for simultaneous multislice imaging [1,2]. The main idea is a novel rf pulse that gives each slice a different linear phase profile. Then, when one slice is rephased by the slice gradient, the others are dephased. In previous work, we simply added two truncated sinc pulses for a 2 slice pulse. This assumed a linear response and was suitable only for low flip angles. Here we describe the design for slice multiplexed rf pulses using the Shinnar-Le Roux (SLR) formalism, which takes into account non-linearities and is therefore suitable for all flip angles.

Method: The method is explained by describing an example for a 3-slice multiplex pulse. Three component pulses with differing rephasing requirements are chosen to be combined into a multiplexed pulse: (i) a DBURP1 pulse [3] with rephasing requirement of +0.15 (see Fig 1a), (ii) a pulse with rephasing -0.35 (Fig 1b), and (iii) a pulse with rephasing -0.85 (Fig 1c). Pulses of Fig 1b and c are in-house pulses found by simulated annealing [4]. These pulses were combined into a single multiplex pulse as follows: the A and B polynomials of the component pulses were found using the forward SLR algorithm [5]. Two roots of DBURP1's A polynomial were found to be outside the unit circle. The B polynomials of Fig 1a and c were first modulated to shift their frequency response, then the B polynomials of all 3 pulses were summed together, and the minimum power A polynomial for this summed B polynomial was found using the recipe described by Pauly et al [5]. However, this minimum power A polynomial has all roots inside the unit circle, so the two DBURP1 roots found earlier were manually flipped back outside the unit circle. The combined B and the modified A polynomials were then inverse SLR transformed to obtain the complex 3-slice multiplex pulse (Fig 1d). The same method was used to design a 4 ms 4-slice pulse with rephasing of : +0.15, -0.19, -0.5 and -0.85 (Fig 1e).

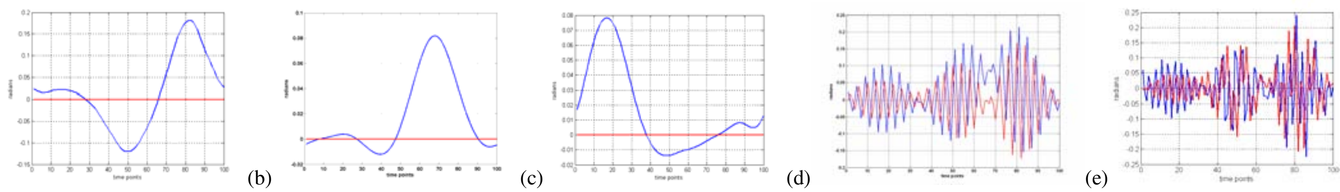

Fig 1(a) (b) (c) (d) (e)

The multiplex pulses were used to image a normal volunteer on a Philips Eclipse 1.5T scanner. The 3-slice pulse sequence is shown in Fig 2. Acquisition parameters were: Matrix 256 × 256, slice thickness = 2.8 mm, TR = 200 ms, Flip angle = 90°. For 3-slices, TE = 5.3, 7.6 and 9.9 ms. For 4-slices, TE = 5.3, 7.6, 9.9 and 12.2 ms.

Results: Using Matpulse 2.4 [6], Bloch simulations were performed of the component pulses and compared with the multiplex pulse (see Fig 3). Note that the response of multiplex pulse for the rephased slice retains nearly exactly the profile of the component pulses. Figures 4 and 5 show in-vivo results.

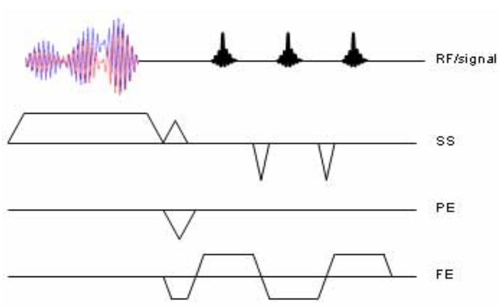

Fig 2. Pulse sequence for 3 slice multiplex pulse

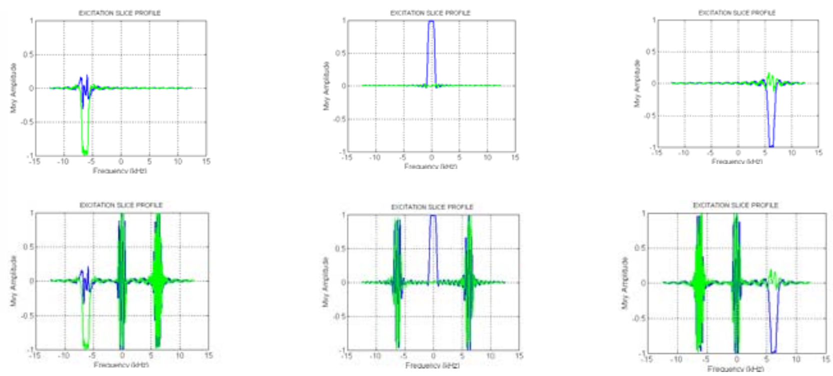

Fig 3. Top half shows simulation of rephased component pulses of 3-slice pulse; bottom half shows simulation of combined 3-slice pulse with the same rephasing. Rephasing was (a) +0.15 (b) -0.35 (c) -0.85.

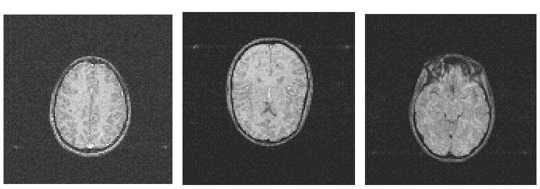

Fig 4. In-vivo brain images using 3-slice pulse sequence of Fig 2.

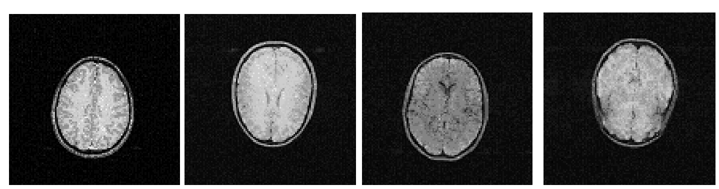

Fig 5. In-vivo images using 4-slice pulse sequence.

Discussion: In previous work, a 2-slice multiplexed pulse was formed by simply adding two pulses together [2]. This is unsatisfactory as it assumes linearity, which can be expected to break down at high flip angles, and as more pulses are added together. The method described here exploits SLR formalism, where the B polynomials of component pulses *can* be added together linearly, with the non-linearities taken care of by the inverse SLR transform. Disadvantages of the slice-multiplexed pulse for imaging are: (i) slices have different TE (ii) slices have different slice profiles and (iii) crosstalk between slices due to incomplete rephasing because of field inhomogeneities, although Figures 4 and 5 show minimal crosstalk is achievable in practice. We find that for a 4 ms pulse length, rephasing lobes should be < +0.2 and > -0.85 for acceptable slice quality, and the minimum dephasing between slices is ≈ 0.35. This implies a maximum number of 4 slices can be multiplexed in a 4 ms pulse. Multiplexed pulses may allow faster multislice imaging, e.g. in a gradient echo sequence, to image 4 slices, the multiplexed sequence will be faster than a conventional sequence if its total time for one view of (1 multiplexed pulse + 1 phase encode + 4 readouts) is less than (4 conventional pulses + 4 phase encodes + 4 readouts).

References: [1] Lee KJ et al. Proc ISMRM (2005) #2397 [2] Lee KJ et al. MRM (2005) 54:755-60. [3] Wu X et al MRM (1991) 20:165-170 [4] Geen H, Freeman R. JMR (1991) 93:93-141 [5] Pauly J et al IEEE TMI (1991) 10:55-65. [6] Matson GB. MRI (1994) 12: 1205-1225.

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