Optimisation of functional signal changes for SSFP

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Purpose. Although gradient echo EPI is the dominant pulse sequence for fMRI applications gradient recalled techniques with TR<T2 are of relevance in a number of situations: the FLASH sequence is still occasionally used to obtain (high spatial resolution) undistorted fMRI images; the PRESTO technique combines elements of both FLASH and EPI and the use of SSFP sequences has been explored both in terms of off-resonance sensitivity to deoxyhemoglobin-induced frequency shifts (1,2)and with regard to BOLD induced signal changes (3). In short, both the S1 and S2 signals of the steady state are used for fMRI, but to date the intrinsic sensitivity of these signals to BOLD-induced changes in T2 has not been calculated. This abstract calculates for the first time the functional sensitivity of these signals, which will be present over and above any T2* contrast added by the use of a non-zero echo time. Optimum values for the flip angles and repetition times are then obtained for a number of realistic situations

Theory. Following established theory (4,5) the following expressions were obtained for the S1 and S2 signal intensities:

$$S_1 = M_0 \sin\alpha(1-E_1)\frac{C-E_2(B-A)}{AC}$$

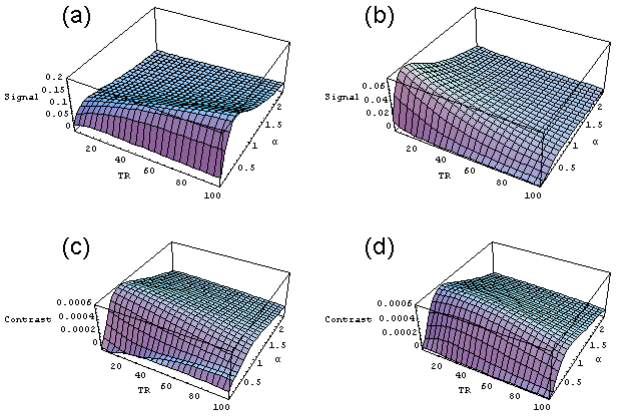
$$S_2 = M_0 \sin\alpha(1-E_1)\frac{E_2(B-A)-E_2^2 C}{AC}$$

Where

$$E_1 = \exp\left(-TR/T_1\right);\ E_2 = \exp\left(-TR/T_2\right);\ B = 1-E_1\cos\alpha - E_2^2(E_1-\cos\alpha);\ C = E_2(1-E_1)(1+\cos\alpha);\ A = \sqrt{(B^2-C^2)}$$

Using Mathematica (Wolfram research) these expressions were then differentiated with respect to T2 to obtain the differential BOLD contrast. The optimum values of the TR and alpha which maximised this contrast were then obtained numerically. The considerable algebraic complexity of the expressions made it impossible for Mathematica to solve this problem analytically.

Results. The figure shows curves as a function of α and TR generated for tissue with relaxation times similar to those of grey matter at 3 T (T1=1300 ms; T2=80 ms). (a) gives the S1 curve; (b) the S2 curve; (c) the differential contrast for S1 and (d) the differential contrast for S2 (note that the differentiation is with respect to T2 and hence that the curves (c) and (d) do not simply represent the slopes of (a) and (b). The *z*-axis in (a) and (b) is given in units of M0, whereas in (c) and (d) it is the normalised contrast. It is clear that for the S1 signal the maximum signal change with respect to T2 is displaced with regard to the maximum intensity. Neither the S1 nor the S2 contrasts show a very strong dependency on TR, which is particularly the case for S2, however the dependency on α is stronger. The table shows optimal values for grey matter at field strengths of 1.5T, 3T and 7T. For the S1 signal the maximum contrast is obtained in the limit as TR tends to zero. The maximum contrasts are similar for S1 and S2 but for S2 the optimum TR would seem to be just under a quarter of the T2 value. As expected, as T1 lengthens the optimum α falls.



		1.5 T (T1 1000; T2 80)	3 T (T1 1300; T2 80)	7T (T1 2000; T2 60)
S1	α (radians)	0.82	0.73	0.44
	TR (ms)	~0	~0	~0
	dS/dT2	0.0007	0.0006	0.0006
S2	α	0.71	0.63	0.45
	TR	18	18	14
	dS/dT2	0.0007	0.0006	0.0006

Discussion. The functional contrast generated by both signals is fairly weak, and for the S1 signal typically acquired at TE=T2* the additional contribution of T2 weighting is probably negligible. The optimum contrast for the S2 signal is obtained for much shorter TRs than the TE that is optimal for a single spin echo (TE=T2). However even when the potential averaging effect is taken into account the sensitivity will be lower. In conclusion it is safe to conclude that non-BOLD strategies for fMRI that utilise the SSFP signal are unaffected by BOLD contamination.

References.

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