Dependence of Inflow Effect in BOLD fMRI Signal on Magnetic Fields

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Introduction

Inflow contribution on BOLD-fMRI signal at 1.5 T was investigated by Gao et al. [1]. However, the inflow effects with blood volume variation on multiple magnetic fields have not been explored. In the present report, the influences of inflow combining with vasodilation were simulated for typical gradient-echo echo planar imaging (GE-EPI) sequence on blood oxygenation level dependent (BOLD)-fMRI signal. The effects of magnetic fields as well as flip angles were simulated in this work. The simulation result showed that with higher magnetic fields or flip angles, the inflow effect could produce higher signal change during stimulated state. In contrast to previous report, the induced signal change by inflow is not suitable to be neglected.

Methods

In the following analysis, only the through-plane plug flow was considered in a single-slice fMRI experiment. To properly model the capillary-surrounding conditions, we chose the parameters listed below: steady blood flow velocity = 0.1 cm/s, resting CBV = 4.59% which varies with inflow velocity according to the equation: $(CBV/CBV_0) = (CBF/CBF_0)^{0.38}$ [2, 3], repetition time (TR) = 2 s, and slice thickness (L) = 6 mm. The relative signal change ($\Delta S/S$) could be determined by Eq.[1], in which v and f are the CBV and flow velocity at stimulated state; v_0 and f_0 are the CBV and flow velocity at steady state; $M_b(f_0)$ and M_t denote the blood and tissue magnetization at steady state. The flow velocity was increased from 0% to 90% during stimulated state whereas the CBV was increased from 0% to 27.6%. Assuming the blood population within the segment would be completely replaced when velocities exceeding L/TR, the magnetization of inflow spins could be simulated by Eq.[2] where M_z is the longitudinal magnetization before the echo time (TE), and m is total number of subpopulation existing in the blood occupancy of the imaging slice (the spins in each subpopulation experienced the same number of RF pulses), n denotes the number of RF pulses that has been experienced in the subpopulation, and the Δ_n is the volume fraction of n[th] subpopulation. M_z of GE-EPI in the equilibrium state was described as Eq.[3]. Table 1 shows the adopted relaxation times of blood and tissue at different field strength [4—6]. The analyses can be divided into 2 parts for examining distinct issues: 1) the effect of flip angle at 3T, 2) the comparison for multiple field strengths. Concerning the 1[st] part, the adopted flip angles were 30°, 45°, 60°, 78°, and 90° where 78°is the Ernst angle for 3T. In the 2[nd] part, different relaxation times were utilized in the simulation under multiple magnetic fields. The Ernst angles (89°/84°/78°/72° for 1/1.5/3/4 T, respectively) were adopted for each field.

Table 1. Adopted relaxation times based on field strength in the present simulation. (unit: ms)

	T_1^b	T_1^t	T_2^{*b}	T_2^{*t}
1T	800	500	180	100
1.5T	1350	900	140	70
3T	1510	1300	90	40
4T	1900	1720	70	30

$$\frac{\Delta S}{S} = \frac{[v \cdot M_b(f) - v_0 \cdot M_b(f_0)]}{v_0 \cdot M_b(f_0) + (1 - v_0) \cdot M_t} \quad [1]$$

$$M_b(f) = \begin{cases} \sum_{n=1}^{m} M_z^n \cdot e^{-TE/T_2^{*b}} \cdot \Delta_n & f_0 < f < L/TR \\ M_z^1 \cdot e^{-TE/T_2^{*b}} & f > L/TR \end{cases} \quad [2]$$

$$M_z = M_0 \cdot \frac{\left(1 - e^{-TR/T_1^b}\right) \cdot \sin\theta}{1 - \cos\theta \cdot e^{-TR/T_1^b}} \quad [3]$$

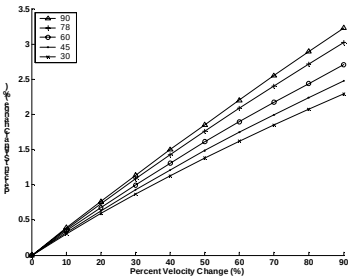

Figure 1. Inflow effect (signal change v.s. blood velocity) on GE-EPI with different flip angles at 3 Tesla. Dynamic CBV varies along with the variation of inflow velocity

Results

The influence of flip angle at 3T was shown in Fig. 1. The flow contribution was increased monotonically with the flow velocities and adopted flip angles. Considering typical 50% increase of flow velocity, the signal changes were among 1.38% to 1.85% corresponding to 30° to 90° of flip angle. The increase of signal change could be up to 3.23% at most (Δf = 90%). Fig. 2 showed the inflow-induced signal changes for each magnetic field on GE-EPI sequence. Even though the Ernst angle decreased in the high fields, the inflow contribution was also ascending with the field strength (1.23%, 1.51%, 1.76%, 2% for 1T, 1.5T, 3T, 4T, respectively). At 4T, the inflow with 90% flow change could provide 3.4% signal change during stimulated state.

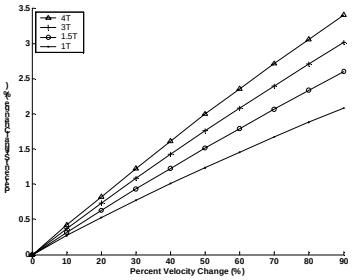

Figure 2. Inflow effect of GE-EPI on multiple magnetic fields (1T, 1.5T, 3T, and 4T) with their Ernst angles. Dynamic CBV varies along with the variation of inflow velocity.

Conclusion & Discussion

Gao et al. reported that the through-plane flow at 1.5T only introduced the signal change less than 0.2% under 50% of flow increase [1]. However, in our simulation results including CBV variation, the corresponding signal change induced by inflow would be overwhelmingly enlarged to 1.3 to 3.4% in stimulated state. Therefore, the assumption of negligible inflow contribution in GE-EPI might not be suitable after considering the CBV variation during stimulated state because the corresponding signal change was also becoming significant. The inflow effects of flip angle and magnetic fields were simulated in this work. The discrepancies between flip angles were not shown obviously (0.42% differentiation of 30° to 90 °) while that of field strengths were relatively strong (0.77% from 1T to 4T).

Albeit that large signal changes induced by inflow effect were reported here and may have significant influence on fMRI signal, several factors in this simulation may introduce slight overestimations. At first, all the flow was assumed to be through-plane flow which affects the fMRI signal most. Secondly, the plug flow type was assumed rather than laminar flow although the difference seems to be negligible in using long TR sequences (such as EPI, comparing to short TR sequences like FLASH). Thirdly, this simulation focuses on the small vessel regime rather than the cortical draining veins. The detailed phenomenon will be investigated further to retrieve the intrinsic fMRI signal without the inflow contribution.

References

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