

Biophysical Principles and Models of SSFP Functional MRI Contrast Mechanisms in the Brain at High and Ultra-High Magnetic Fields

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Purpose: This work is based on the review of the basics of functional MRI (fMRI) contrast mechanism in the brain using the balanced steady-state free precession (bSSFP) regime. First, the basics of bSSFP sequence are reviewed and then different classes of bSSFP fMRI are introduced. Thereafter, details about the signal models for the functional contrast in the brain generated using bSSFP are given. Benefits of using the convolution model in the pass-band bSSFP fMRI are presented and new ideas about using novel signal processing methods, which could be employed for functional contrast modeling in SSFP, are suggested. In the end, a recently introduced nonbalanced SSFP method for fMRI is also presented for comparison with bSSFP methods. This work would enable understanding the functional contrast in the brain using distortion-free, high-resolution SSFP fMRI methods feasible for high and ultra-high magnetic fields.

Outline of Content: In the bSSFP sequences, all imaging gradients have net area equals to zero during TR . Consequently, the fully refocused gradients in bSSFP imply that only the off-resonance precession can induce the phase accrual during TR (residual dephasing). It is important to emphasize that the gradient induced dephasing within a voxel diminishes in the case of bSSFP; hence, bSSFP is relatively less sensitive to motion. The distinguishing characteristic of the bSSFP scheme is the description of the magnetization precessing at a single angle (ideally) during TR . Thus, signals coming from the isochromats precessing at different resonance frequencies can be differentiated. The bSSFP signal is a complex function of T_1 , T_2 , TR , precession due to the resonance frequency offset, the flip angle and the phase of the RF pulse. Recently, different bSSFP based fMRI schemes for the brain have been focus of attention. The bSSFP fMRI methods can be divided into two classes, i.e., the transition band methods [1], [2] and the pass band methods [3], [4]. The transition band methods utilize the oxygenation based functional contrast detection in the steep magnitude or phase transition region of the bSSFP off-resonance spectrum, where the functional contrast in the brain is generated due to the resonance frequency shift induced by deoxyhemoglobin following neuronal activity. On the other hand, the pass band methods are based on the functional contrast detection in the flat portion of bSSFP off-resonance spectrum and here the functional contrast in the brain is obtained by the nonrefocused dephasing due to the large scale off-resonance effects by deoxygenating hemoglobin. This situation arises when the off-resonance effects are in the spatial scale of the water diffusion distance during TR . Stimulated echo pathways differentiates this bSSFP contrast mechanism from spin echo. In short, the functional contrast mechanism of pass-band bSSFP could originate from the intravascular components, extravascular components and decrease in diffusion of water molecules in addition to decrease in deoxyhemoglobin [4], [5]. In [6], signal and noise characteristics of bSSFP fMRI are compared with gradient echo at multiple field strengths and equivalent signal changes are shown at long TR . On the other hand, functional contrast is achieved in bSSFP at short TE and TR , but not in the case of gradient echo. It has been concluded that pass-band bSSFP reflects T_2 BOLD at short TR and T_2^* BOLD at long TR [6]. In addition to T_2 effects, the contrast originating from the off-resonance effects should be considered for pass-band bSSFP. Therefore, the functional contrast in bSSFP is modeled in [7] by convolving the theoretical bSSFP signal profile and the underlying frequency distribution profile. Monte Carlo simulations of voxel signal in the presence of vascular network containing deoxygenated blood are used to correct the convolution model by including the effects of diffusion, which can alter the apparent T_2 and linespread. Hence, the collective signal behavior of the transition band and the pass band is represented by this model. The theoretical signal profile is symmetric about the on-resonance frequency in the case a single T_1 , T_2 and resonance frequency within a voxel. However, chemical shift, different microstructural boundaries and compartments in tissue, generate inhomogeneous voxel frequency distribution, which in turn produce asymmetries in the signal profile obtained through bSSFP. A method has been proposed in [8] for detecting these frequency distribution asymmetries in gray matter, white matter and muscle by using the asymmetry in the bSSFP signal measured at a range of frequencies. These asymmetries can be utilized as a sensitive probe of tissue microstructure. Additionally, another method is proposed in [9] to quantifying the larger asymmetries observed in white matter. These quantified maps are compared with a diffusion-tensor atlas. Furthermore, multiple TR measurements provide the evidence that the asymmetries are characterized by relatively small frequency shifts. Although, convolution modeling scheme combined with the Monte Carlo simulations is a feasible approach, application of other ideas based on novel signal processing methods, such as, state-space filtering and particle filtering, would be briefly introduced for bSSFP. So far, emphasis has been given on the bSSFP fMRI, another method is introduced in literature recently [10], which enables T_2 -weighted 3D fMRI using S_2 -SSFP at 7 Tesla. In the end, this method is compared with the aforementioned bSSFP methods.

Summary: A comprehensive introduction of fMRI using the balanced and non-balanced SSFP approaches is given in this work. Application of corrected-convolution model for fMRI contrast in bSSFP has been reviewed in detail. The feasibility analysis of bSSFP and S_2 -SSFP fMRI methods at high and ultra-high magnetic fields is given. Furthermore, the potential of state-space filtering and particle filtering for bSSFP fMRI contrast modeling has been discussed.

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