Correction for T1 effect incorporating flip angle estimated by Kalman filter in cardiac-gated fMRI

Jaemin Shin[1], and Xiaoping Hu[1]

[1]*Biomedical Engineering, Georgia Tech/Emory University, Atlanta, GA, United States*

INTRODUCTION

Physiological noise is one major factor compromising the detection sensitivity of fMRI [1, 2]. To overcome cardiac pulsation related artifact, cardiac-gated acquisition has been utilized with correction for T1 related signal fluctuation (T1 effect) due to variation of the cardiac cycle but it is only valid for the flip angle of 90° [3, 4]. B1 inhomogeneity can often cause a significant variation in flip angle, e.g., 65° to 105° over the brain volume for a nominal flip angle of 90° at 3 T [5, 6]. Moreover, a nominal flip angle less than 90° may be desired for better SNR based on the Ernst angle. In this study, we developed a generalized correction technique for T1 effect incorporating actual flip angle, estimated from fMRI dataset itself using unscented Kalman filter [7]. The new technique is demonstrated with simulated data and *in vivo* data.

THEORY and METHODS

In an fMRI time series, the MR signal for k^{th} measurement is given by

$$m_k = M_0(\sin\alpha)e^{-TE/T2^*_k} + \left[m_{k-1}(\cos\alpha) - M_0(\sin\alpha)e^{-TE/T2^*_k}\right]e^{-TR_k/T1} \quad (1)$$

where α is flip angle and M_0 is the equilibrium magnetization. For the special case of α being 90°, the MR signal is simplified to

$$m_k = M_0\, e^{-TE/T2^*_k}\left[1 - e^{-TR_k/T1}\right]$$

With two measures at TR_1/TR_2=1s/20s, one can estimate T1 by $-TR_1 / \ln(1 - m_1/m_2)$ and correct for the T1 effect by multiplying with $[1 - e^{(-TRavg/T1)}] / [1 - e^{(-TRk/T1)}]$ (denoted "T1 only" approach) [4]. In the presence of spatial inhomogeneity of B1, this correction is not valid over the entire volume of brain even for the nominal flip angle of 90°. In the present work, the state-space model for MR signal, previously described in Kalman filter framework [8], was extended to estimate flip angle and T1 simultaneously from fMRI data. With these estimates, the corrected time series is calculated from Eq. (1) (termed "T1 & flip angle" approach)

Simulation data: Simulated cardiac-gated fMRI series were generated from Eq. (1) for a range of flip angles (60° ~ 110°) and T1 (800 ms ~ 2000 ms) with the addition of T2* related change (3%) based on timing information of the experiment described below. Noise was added resulting in a temporal SNR (tSNR) of 90 with a mixture of 70% white noise and 30% AR(1) noise. Corrections for T1 effect were performed using "T1 only" and "T1 & flip angle" approaches. tSNR was calculated on the corrected datasets.

In vivo data: All MRI experiments were conducted on a 3T Siemens Tim Trio scanner (Siemens Medical Solutions, Malvern, PA). Subjects underwent two functional MRI scans: 1) cardiac-gated scan and 2) ungated scan using EPI sequence with the following parameters: TE=30ms, FA=90°, FOV=22 cm, GRAPPA with PE=2, 2×2×3 mm^3, and 8 axial slices with 20% gap. For ungated scan, average TR of gated scan was used. Our stimuli consisted of five 30-TR blocks of rest with gazing fixation interleaved with four blocks of visual stimulation (alternatively left and right visual fields) using a half-filled inverting checkerboard at 8 Hz. The data were first corrected using the previous method and our new method. fMRI preprocessing included dropping the first 10 volumes, motions correction, linear detrending, and 3 mm smoothing. A multiple regression analysis was performed using regressors representing the two visual stimulus conditions as well as motion parameters to derive the fMRI activation map.

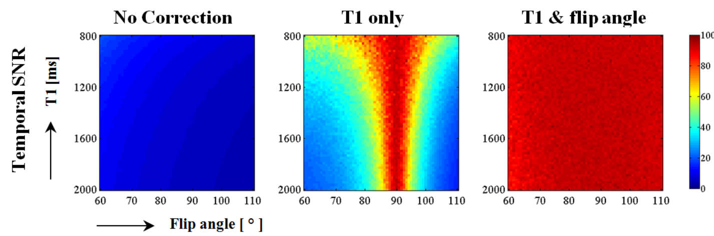

Figure 1. Temporal SNR in simulated data for varying flip angle and T1

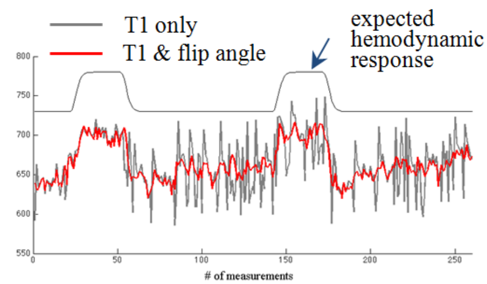

Figure 2. *In vivo* time series of a representative voxel in right V1 from gated and corrected datasets

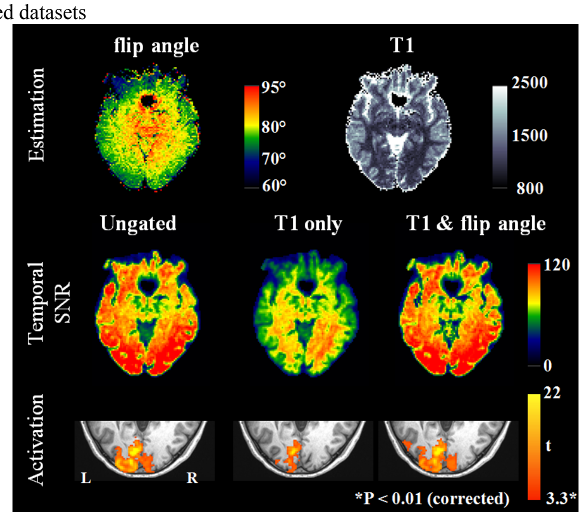

Figure 3. *In vivo* results from the same slice; (top) Estimated flip angle and T1 using Kalman filter, (middle) temporal SNR on preprocessed data and (bottom) Activation map for right field stimulus at P < 0.01 (corrected)

RESULTS and DISCUSSION

Figure 1 shows tSNR map in simulated data as a function of flip angle and T1. While tSNR values in the "T1 only" approach show a significant increase near the flip angle of 90°, tSNR values in the "T1 & flip angle" result exhibit an increase across the entire range of flip angle. This clearly indicates that the "T1 only" approach is effective only near the true angle of 90°. Representative time series from *in vivo* data are plotted in Figure 2. The estimated flip angle shows a wide variation and ranges from 62° to 95° in the slice (Figure 3), consistent with previous reports [5, 6]. Because of this variation, for the "T1 only" approach, tSNR values in peripheral area are substantially lower than in central area. Activation maps clearly demonstrate that the "T1 & flip angle" approach is superior over the "T1 only" in statistical significance and spatial extent in left V1. The technique of estimating flip angle using Kalman filter can be utilized in other applications where a flip angle (or B1) map is needed.

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