Improved Correction for TR Variation in Cardiac Gated fMRI Using Unscented Kalman Filter

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INTRODUCTION

Physiological noise, such as respiration-induced signal variation and cardiac pulsatility artifacts, is major factor that reduces the detection sensitivity of fMRI. Respiration effects can be successfully reduced with retrospective correction. However, the motion of the brain itself, as well as pulsatile flow of CSF and large vessels, makes retrospective correction of cardiac noise difficult, especially in the brainstem. To overcome this problem, cardiac gated acquisition has been suggested as a means to freeze pulsation induced brain movement [1]. The primary difficulty with this strategy lies in the TR inconsistency due to the variation of the cardiac cycle. This TR variability introduces T1-dependent signal variation (approximately 3% with a TR that has a 10% variation around 10%, T1 = 1 sec and FA=90°, for gray matter) which may overwhelm the BOLD response. In addition, because of underlying spin physics associated with the evolution of magnetization, correction for the effect of variable TR is not straightforward for non-90° flip angles. In this work, we describe a generalized correction method applicable to any flip angle based on parameter estimation using a nonlinear state-space model with an Unscented Kalman Filter (UKF), which is a recursive minimum mean square error (MMSE) estimator that utilizes the optimal Gaussian approximate Kalman filter framework [2].

THEORY

The Kalman filter framework is suitable for estimation in MR applications due to its recurrent nature and the absence of a stationarity assumption. The state-space model for fMRI time series is as follows:

State

$$M_1(r;k) = M_1(r;k) + v_1(k-1)$$

$$T_1(r;k) = T_1(r;k) + v_2(k-1), \quad \mathbf{v}(k) = [v_1(k), v_2(k)] : N(\mathbf{0}, \mathbf{R}_k)$$

$$m(r;n) = M_1(r;k) + [m(r;k-1)\cos a - M_1(r;k)]\exp(-t(k)/T_1(r)) \quad (1)$$

Observation

$$y(r;k) = m(r;k) + w(k), \quad w(k) : N(0, s^2_k)$$

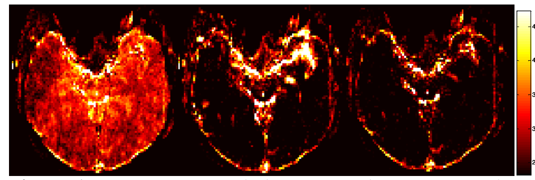

Figure 1. The standard deviation map during the rest period of (a) the cardiac gated method without T1 correction, (b) the fixed TR and (c) the cardiac gated method with T1 correction

where $\{y(r;k)\}$ is an observed image intensity at time point k and 3D position r, while $\{m(r;k)\}$ is the true image intensity. $\{T_1(r;k)\}$ is the longitudinal relaxation time, a is the flip angle and $t(k)$ is the actual TR determined by the length of the cardiac cycle. In Eqn. 1, $M_1(r;k) = M_0 \sin(a)\exp(-TE/T_2*(k))$, where M_0 is the equilibrium magnetization. $\mathbf{v}(k)$ and $w(k)$ denote state and observation noise, respectively. For T1 correction at an arbitrary flip angle, two parameters, $M_1(r;k)$ and $T_1(r;k)$, are simultaneously estimated with UKF. The objective of this estimator is to minimize the prediction error of image intensity, $E[(y(k)-m(k))^2]$, at position r rather than T1 prediction error, $E[(T_1(k)-T_1^{true}(k))^2]$. The UKF captures the posterior mean and covariance accurately in the presence of non-linearity, with errors only introduced in the 3rd and higher order moments[2].

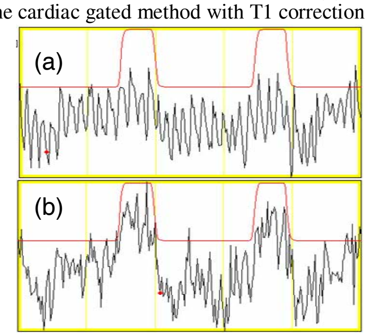

Figure 2. Time courses of a representative position from the gated data. (a) without T1 correction and (b) with T1 correction

METHODS

Kalman filter: We acquired a preparation scan, which was used as an initialization value of $M_1(r)$ for the UKF algorithm. An annealing method was used for process noise updating [2]. This method set the process covariance to a fixed diagonal value, which may then be "annealed" toward zero as estimation continues. The final state estimation was used as a static parameter to correct each image in the series. Specifically, we subtracted the estimated additional T1-dependent signal variation from the original series. The reference time series was generated using the signal equation (1) with a fixed TR as a median value of t(k). ReBEL (http://choosh.ece.ogi.edu/rebel/) and in-house MATLAB programs (http://www.mathworks.com) were used to carry out the UKF.

Image Acquisition & Paradigm: All MRI scans were performed on a Siemens 3T Trio MR scanner. Data was acquired for two subjects using an EPI sequence with TE=30ms, FOV=22cm and matrix size of 128 x 128 with 6/8 partial Fourier for both sessions. For each subject, one scan was acquired using the TR of one heartbeat for the cardiac gated method and the other scan was acquired using the fixed TR chosen by the average of the RR interval . Our stimuli consisted of five 30 s blocks of rest with fixation interleaved with four blocks of visual stimulation (two blocks for both left and right visual fields) using a half-filled inverting checkerboard at 8 Hz for a total scanning time of 4min 30 sec.

fMRI Data Analysis: AFNI (http://afni.nimh.nih.gov/afni/) and several in-house MATLAB programs were used in data analysis. Data preprocessing included spatial smoothing (FWHM=2.5mm), motion correction and linear detrending in AFNI. RETROICOR was performed to remove respiratory fluctuation in both data sets [3].

RESULTS and DISCUSSION

Figure 1 shows the standard deviation (SD) maps for (a) the cardiac gated method without T1 correction, (b) the fixed TR, and (c) the cardiac gated method with T1 correction during the rest periods. The correction significantly reduced signal variation. The average standard deviations were 29.69, 25.49, and 23.87 for Figs. 1 a, b, and c, respectively. The fixed TR scan shows high signal variation in regions corresponding CSF and large vessels. In Figure 2, representative time courses are plotted along with ideal responses. Activation maps (Fig. 3) show larger activation areas as well as higher F-values for the gated method with correction. In addition, using the gated method enabled activation detection at regions in the brain stem such as optic tract and superior colliculus.

ACKNOWLEDGEMENT

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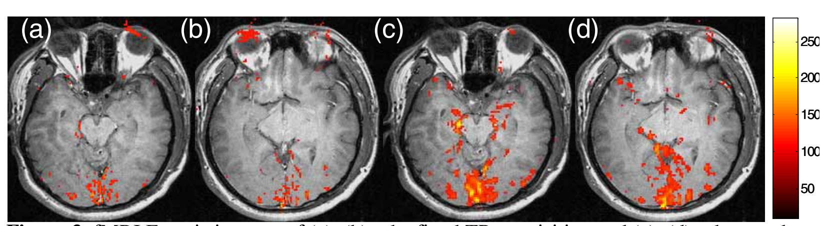

Figure 3. fMRI F-statistic maps of (a), (b) : the fixed TR acquisition and (c), (d) : the gated method with correction. The clear activation of brainstem, such as superior colliculus and optic tract, was observed in the gated method.