Optimization of Echo Time in Direct Detection of Neuronal Currents with MRI

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Introduction

Various experiments have been performed to use MRI to directly detect magnetic fields produced by neuronal currents (termed ncMRI)[1]. However, feasibility of ncMRI has not been completely demonstrated due to limited sensitivity of MRI to neuronal currents. To increase the possibility of detecting ncMRI signal, it is necessary to improve the detection method to achieve higher detection sensitivity, and one improvement is to optimize choice of echo time (TE)[1]. The purpose of this study was to estimate the optimal TE for ncMRI experiments using gradient echo EPI pulse sequence. In this work, by modeling the contrast-to-noise ratio (CNR) of ncMRI signal, we obtained the optimal TEs for detecting ncMRI magnitude and phase signals *in-vivo*. These results will assist in future ncMRI experiments for selecting the optimal TE to achieve the best detection sensitivity.

Methods

The optimal TE was calculated by modeling the relationship between CNR of ncMRI signal and TE, and then selecting the TE that corresponds to the maximum CNR. These calculations were performed for both magnitude and phase ncMRI signals.

The CNR of ncMRI magnitude (CNR_S) and phase (CNR_ϕ) signals are expressed as[2]:

$$CNR_S = \delta \cdot TSNR_S \quad \text{(Eq. 1)}$$

$$CNR_\phi = \Delta\phi \cdot TSNR_S \quad \text{(Eq. 2)}$$

here δ and $\Delta\phi$ are the relative magnitude signal change and phase shift induced by ncMRI effects, respectively. According the simulation results of the previous theoretical models[3-5], δ and $\Delta\phi$ are TE dependent and can be expressed as a exponential function of TE approximately:

$$\delta = c_1 (TE)^\alpha \quad \text{(Eq. 3)}$$

$$\Delta\phi = c_2 (TE)^\beta \quad \text{(Eq. 4)}$$

where c_1, c_2, α, and β are constants. The values of α and β obtained from different ncMRI models[3-5] are different and vary in 1.4-2.0 and 0.8-1.2, respectively.

$TSNR_S$ in Eqs. [1] and [2] is the temporal signal-to-noise ratio of the MRI magnitude signal at resting state. According to the noise model of MRI[6], the $TSNR_S$ for gradient echo EPI pulse sequence is expressed as:

$$TSNR_S = \frac{1}{\sqrt{\sigma_{S_0}^2 - 2TE \cdot CC_{S_0 R_2^*} \cdot \sigma_{S_0} \cdot \sigma_{R_2^*} + TE^2 \cdot \sigma_{R_2^*}^2 + (e^{TE \cdot R_2^*} \cdot \sigma_T)^2}} \quad \text{(Eq. 5)}$$

where S_0 and R_2^* ($= 1/T_2^*$) are the initial amplitude of MRI signal (i.e., signal intensity at TE = 0 ms) and transverse relaxation rate, respectively. Since T_2^* can vary in different brain regions, $TSNR_S$ for different T_2^* values (= 0-80 ms, interval = 1 ms) are calculated in this study. σ_{S_0} and $\sigma_{R_2^*}$ are the noise from S_0 and R_2^* fluctuations, which are induced by system instability and physiological noise, and $CC_{S_0 R_2^*}$ is the cross-correlation coefficient between S_0 and R_2^*, σ_T is the thermal noise normalized to S_0. σ_{S_0} (normalized to S_0), $CC_{S_0 R_2^*}$, $\sigma_{R_2^*}$ and σ_T are constants and equal to 1.86%, 0.101, 0.63 s^{-1}, and 0.66% in gray matter of human brain at 3T, respectively[6].

From Eqs. [1-5], the dependence of CNR on TE was calculated for magnitude and phase signals with different T_2^* values. Then the maximum CNRs were obtained and the corresponding TEs will be the optimal TEs for detecting the ncMRI signals.

Results and Discussion

Fig. 1a shows the CNRs of ncMRI signal in human brain for TE = 0-150 ms at 3 T when T_2^* = 40 ms, which is the typical T_2^* value in human brain at 3 T[7]. The results show that the CNR of magnitude/phase signal increased with TE first and reached maximum at 92 ms/56 ms, and then decreased with further increase in TE. Therefore, when T_2^* = 40 ms, the optimal TEs for detecting the ncMRI magnitude and phase signals in human subjects at 3 T are 92 ms and 56 ms, respectively.

The value of optimal TE for magnitude (phase) imaging depends on T_2^* and α (β). Fig. 1b shows the dependence of optimal TEs on T_2^* when α = 1.4-2.0 (interval, 0.3) and β = 0.8-1.2 (interval, 0.2). It is found that the optimal TEs increased with T_2^* for both magnitude and phase ncMRI signal, but the optimal TE for magnitude signal increased more rapidly with T_2^* than that for phase signal. For a given T_2^*, the optimal TEs increased with the increase of α and β, and the optimal TE for detecting magnitude signal is longer than that for phase signal. The difference in optimal TE between magnitude and phase ncMRI signals is enlarged with the increase of T_2^* value. The difference of optimal TE between magnitude and phase imaging implies that the highest CNRs for magnitude and phase ncMRI signals can not be achieved simultaneously with a single TE value. To maximize the detection sensitivity to both signals in one MRI scan, ncMRI magnitude and phase images need to be acquired with a dual-echo pulse sequence.

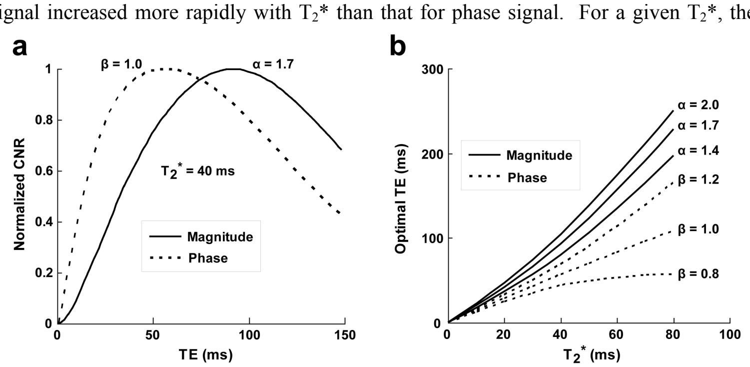

Fig. 1 Dependence of CNR on TE in human brain at 3 T (a) and dependence of optimal TE on T_2^* for different α and β (b).

References

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