Correction for the echo-shifting related artifacts in T2* mapping

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Introduction

T2* mapping, a commonly performed MR procedure, is useful for characterizing tissue properties, such as the iron load and blood oxygenation level. T2* mapping can be achieved by exponentially fitting the TE-dependent signal intensities of gradient-echo images and gradient-echo EPI. However, our analysis and experimental data show that, in the presence of background susceptibility field gradients (e.g. near the air-tissue interface), the echo-shifting effect and TE-shifting effect will make the calculated T2* maps inaccurate. Accurate T2* mapping can be achieved only after (1) quantifying the echo-shifting effect, (2) correcting for the TE-shifting effect during T2 fitting, and (3) excluding the data affected by echo-shifting induced signal loss.

The echo-shifting effect and TE-shifting effect in gradient-echo imaging and gradient-echo EPI

The pulse sequences of full-Fourier gradient-echo imaging and EPI are designed in such a way that the peaks of the k-space echo energy are located at the center of the sampling windows. However, when there exists a susceptibility field gradient, the k-space energy peaks deviate from the center of the sampling window (ref.1). This is termed **echo-shifting effect**. The echo-shifting effect along the phase-encoding direction will result in changes of the effective TE in EPI [ref.1]. Similarly, the echo-shifting effect along the readout direction will induce changes of the TE in gradient-echo imaging (ref.2). This is termed **TE-shifting effect**. The TE-shifting effect (ΔTE) in gradient-echo EPI and gradient-echo imaging depends on scan parameters and background susceptibility field gradients, as presented in Equations 1 and 2, respectively, in which TE0 is the targeted TE value, ESP is EPI's echo-spacing time along the phase-encoding direction, DW is the dwell-time in gradient-echo imaging, SGP is the susceptibility field gradient along the phase-encoding direction, and SGR is the susceptibility field gradient along the readout direction.

$$\Delta TE_{EPI} = \frac{-SGP \times TE0 \times ESP}{SGP \times ESP + \frac{1}{\gamma \times FOV_{PE}}} \cdots\cdots [1] \qquad \Delta TE_{GRE} = \frac{-SGR \times TE0 \times DW}{SGR \times DW + \frac{1}{\gamma \times FOV_{RO}}} \cdots\cdots [2]$$

It can be seen in Equations 1 and 2 and our phantom multi-TE EPI k-space data (Figure 1a; acquired with a constant background field gradient) that, the amount of TE variation is linearly proportional to the targeted TE value. This targeted TE dependent TE-shifting effect would make the T2* mapping inaccurate. It can also be seen in the reconstructed EPI images (Figure 1b) that, a significant echo-shifting effect may result in severe signal loss artifact in the reconstructed images, which in turns may further degrade the accuracy of T2* measurement.

Quantification of the echo-shifting effect using the k-space energy spectrum analysis algorithm

The echo-shifting effect in both gradient-echo imaging and gradient-echo EPI needs to be first quantified, so that the associated artifacts in T2* mapping can be effectively corrected. Quantification of the echo-shifting effect can be achieved with the k-space energy spectrum analysis algorithm (ref.3), consisting of the following steps. First, a selected number of ky lines of the acquired 2D k-space data are truncated and replaced with the values calculated from the un-truncated ky lines using Cuppen's partial Fourier algorithm. Second, step one is repeated for different numbers of ky replacement, so that multiple images corresponding to different partial Fourier ratios can be obtained. Third, the pixel-wise signal intensities of the images corresponding to different partial Fourier ratios are analyzed. The k-space energy peak location (and thus the echo-shifting effect) in the original 2D k-space data can be determined by identifying the abrupt signal transition in the multiple partial Fourier images. We have successfully applied the k-space energy spectrum analysis method to mapping the echo-shifting effect and TE-shifting effect in phantom and human brain images. For example, TE-shifting maps corresponding to two axial-plane human brain EPI images are shown in Figure 2. There exist significant TE shifting effects in areas near the air-tissue interfaces.

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Correction for the TE-shifting effect

As demonstrated by Figure 1 and Equations 1 and 2, the TE-shifting effect depends on the targeted TE, which in turns make T2* calculation inaccurate. We have developed a procedure to correct for this TE-shifting effect. First, using the k-space energy spectrum analysis method described in the previous paragraphs, the spatially-dependent TE-shifting values (i.e. the TE-shifting maps) are calculated for each of the T2*-weighted images. Second, the corrected TE values for every pixels of the multiple-TE images are used in exponentially fitting the TE-dependent MRI signal intensities. For example, in our 3T phantom study, the uncorrected and corrected TE-dependent signal intensities are presented by red and blue curves, respectively, in Figure 3. We have also applied this procedure to correct for the TE-shifting effect in human brain T2* mapping.

Identification of echo-shifting induced signal loss in T2 mapping*

When the background susceptibility field gradient is very significant (e.g. in areas near the air-tissue interface), the echo energy peaks may be shifted completely outside the k-space sampling window, which in turns results in severe signal loss in the reconstructed images. By analyzing the multi-TE imaging data with the k-space energy spectrum analysis method, this k-space shifting effect can be identified, and its impact on the T2* mapping accuracy can be minimized. For example, the red dots in Figure 4 represent the EPI signals in areas affected by a strong background field gradient. Using the developed procedure, the critical TE value that corresponds to the echo-shifting induced signal loss is identified (arrow). Accurate T2* measurement can be achieved by exponential fitting only the data that are not degraded by the signal loss artifact (blue curve in Figure 4).

Conclusions

When there exists a background susceptibility field gradient, the conventional T2* mapping procedures based on multi-TE imaging is inaccurate, if the TE-shifting effect is not corrected. Using the k-space energy spectrum analysis method and the procedure presented in this article, the echo-shifting related artifacts in both gradient-echo imaging and gradient-echo EPI can be corrected, and accurate T2* mapping can be achieved.

References:

(1) Deichmann R. et al. Neuroimage15:120, 2002. (2) Posse S. Magn Reson Med 25:12, 1992. (3) Chen N et al. ISMRM proceedings 156, 2005.

Figure 1: (a) k-space data (b) EPI images

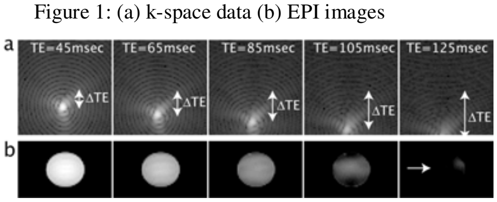

Figure 2 (a) EPI images
(b) TE-shifting maps