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Effect on BOLD Sensitivity Due to Susceptibility-induced Echo Time Shift in Spiral-in Based Functional MRI

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***Abstract*—Susceptibility artifacts induced by the magnetic field inhomogeneity exist near the air/tissue interfaces at the ventral brain in functional magnetic resonance imaging (fMRI). These susceptibility artifacts will cause geometric distortions and signal loss in reconstructed images. Additionally, the in-plane susceptibility gradients will cause a shift in effective echo time, and therefore influence the blood-oxygen-level dependent (BOLD) sensitivity since it is proportional to effective echo time. In this work, we examine the effective echo time shift and the change of the BOLD sensitivity based on susceptibility gradients. The analysis results show that there are regions, such as the orbitofrontal cortex, that suffer from significant loss of BOLD sensitivity using spiral-in trajectory in BOLD fMRI.**

I. INTRODUCTION

MAGNETIC susceptibility is a property that describes the magnetizability of a substance to a magnetic field. Blood-oxygen-level dependent (BOLD) functional magnetic resonance imaging (fMRI) measures the contrast between magnetic susceptibility of baseline and activated states using the magnetic susceptibility differences between deoxyhemoglobin and tissues [1]. However, magnetic susceptibility differences also exist at air/tissue interfaces and will lead to susceptibility artifacts in fMRI. This is due to magnetic susceptibility difference between air and tissue in the ventral brain will cause the non-uniformity of magnetic field when a subject is placed in the MRI scanner.

Several artifacts result from the magnetic susceptibility. For convenience, we group these artifacts into three categories: geometric distortions, signal loss and echo time shift. For the first artifact, many correction methods exist to compensate for susceptibility-induced geometric distortion using a measurement of the distribution of magnetic field which is called field map (FM) [2-7]. A field map is measured by subtracting the phase of two images acquired with different echo times [2-4].

The second artifact, through-plane signal loss, has been addressed by several methods. One of the simple methods is to decrease dimensions of the voxel in slice-select direction [8-10]. Another approach is to utilize devices[11-14], such as a mouth shim coil [13], to improve shimming in orbitofrontal region. The third method, known as Z-shimming method, modifies the slice-select gradient during signal acquisition for compensation [15-17]. Finally, as reported in [18-19], a phase profile across slice in RF pulses can be used to counteract signal dephasing profile during signal acquisition.

Besides the artifact of through-plane susceptibility gradients leading to signal loss, in-plane susceptibility gradients [20-26] can cause a shift in echo time in a gradient echo (GRE) acquisition. Echo time is defined as the time point of peak of the echo, at which the center of k-space was sampled. Therefore, the shift of echo time will influence bulk contrast and BOLD sensitivity of reconstructed image in functional MRI. Compensation of susceptibility-induced BOLD sensitivity losses in EPI acquisition has been addressed in [24]. The effect on spiral acquisitions was discussed briefly in[25]. However, it still remains a critical issue and in this paper, we examine the impact on spiral-in acquisitions. In [26], the effective echo time was found to be longer than designed echo times for spiral-out acquisitions, and shorter for spiral-in acquisitions.

In this paper, we extend the method in [24] to a spiral-in trajectory, and will mainly focus on analysis of the effect of echo time shift on BOLD sensitivity signal. We choose the spiral-in trajectory because of its robustness to signal loss artifacts.

II. THEORY

In this section, we will describe the effective k-space trajectory and the influence on echo time shift in gradient echo acquisition. Then we will analyze the effect on BOLD sensitivity signal in fMRI.

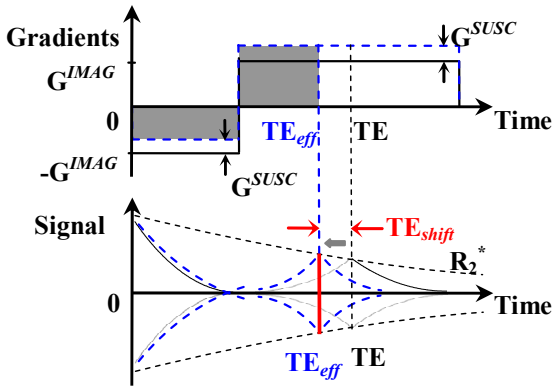

Fig. 1. Effect of echo time shift due to a positive, constant susceptibility gradient in gradient echo fMRI.

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A. *Echo time shift in GRE acquisition*

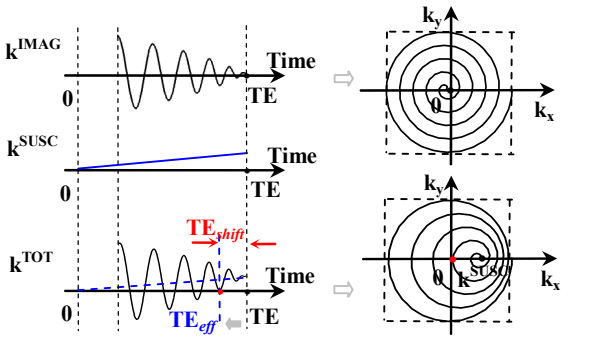
For simplicity, we first consider a 1D case of a positive, constant susceptibility gradient in the X-direction, as shown in Fig. 1 (Note: higher-order susceptibility gradients also exist, but focus of this paper is on the linear components). The susceptibility gradient will create an effective k-space trajectory which will deviate from designed imaging trajectory and the resultant k-space trajectory will be spatially-dependent, as shown in equation (1):

$$G_X^{TOT}(\mathbf{r}) = G_X^{IMAG} + G_X^{SUSC}(\mathbf{r}) \qquad (1)$$

where G_x^{IMAG} is the designed imaging gradient in the X-direction, which is same for every image voxel (solid black line in Fig.1, top); $G_x^{SUSC}(\mathbf{r})$ is a positive, constant susceptibility gradient in X-direction at voxel position **r**; and $G_x^{TOT}(\mathbf{r})$ is net gradient in voxel at position **r**, which is different with the designed imaging gradient (dashed blue line in Fig.1, top).

In the bottom of Fig.1, the dashed blue line shows that the k-space signal will decay slower and the echo will recover faster due to the positive susceptibility gradient $G_x^{SUSC}(\mathbf{r})$ contributed to net gradient $G_x^{TOT}(\mathbf{r})$. Accordingly, the echo will reach its peak earlier (TE_{eff}) than designed echo time (TE). Thus, the existence of a positive susceptibility gradient in this simple 1D example causes TE shift to an earlier time in gradient-echo acquisitions (similarly, a negative one will also cause TE shift to a earlier time in this simple 1D trajectory). Therefore, the sampled signal will not match the expected intensity formed at the intended echo time.

B. *BOLD Sensitivity Change Due to Echo Time Shift*



(a) 1D effect using spiral-in **(b) 2D effect using spiral-in**

Fig. 2. Effect of echo time shift due to susceptibility gradient in X-direction using spiral-in acquisition.

We now examine the effect of susceptibility gradients in the X-direction using spiral-in acquisition as an example. The X-axis gradient of a spiral-in trajectory is shown in Fig.2 (a), where k^{IMAG} represents the original designed imaging k-space trajectory in the X-direction; k^{SUSC} is the k-space trajectory induced by susceptibility gradients in the X-direction; and k^{TOT} is the net k-space trajectory which is effectively applied to the voxel. As shown in Fig.2 (b), the whole k-space trajectory has been shifted and skewed in X-direction, and as a result, the center of sampled k-space has been shifted away from true center of k-space. Therefore, the effective echo time also has been changed to an earlier time due to the change of effective k-space trajectory.

The BOLD signal has a strong dependence on echo time. Therefore, in gradient echo functional MRI, the susceptibility gradients can influence BOLD sensitivity by changing the effective echo time in each voxel. Additionally, if the shift of k-space is large enough, the central portion of k-space may not be adequately sampled so that functional imaging will not be possible [21].

III. METHODS

In this section, we will first mention the experimental setup for measurement of field map. Then we will briefly describe the method to estimate the effective echo time based on effective k-space trajectory due to susceptibility gradients. Finally, we will present the approach used to calculate BOLD sensitivity maps.

The experiment for human subject is performed on a Siemens Allegra 3 Tesla MRI headscanner. The parameters of scan are: matrix size 64×64, FOV 24 cm, 20 slices, slice thickness 5 mm, TE 30 ms, TR 4 s. The field map was estimated from a 2D multiecho GRE acquisition using spiral-in trajectory.

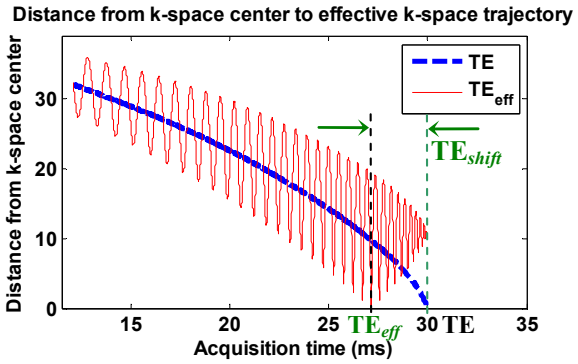


Fig. 3. Estimation of effective echo time based on effective k-space trajectory's distance from k-space center for X-direction using spiral-in acquisition. The dashed blue line represents designed k-space trajectory based on original echo time TE, and the solid red line represents effective k-space trajectory based on effective echo time TE_{eff} (due to susceptibility gradients in X-direction).

To estimate the echo time shifts, we use a method based on calculation of effective k-space trajectory. The main principle is to calculate the minimum distance of the effective k-space trajectory from the origin of k-space to determine the point in trajectory that crosses zero for each voxel. For example, Fig. 3 shows a calculated distance from center of k-space to the original (dashed blue line) and effective (solid red line) k-space trajectories, respectively. As shown in Fig. 3, the minimum distance point will yield the shifted k-space center estimate for each voxel. Then we measure the effective echo

time (TE_{eff}) based on the time point corresponding to the estimated k-space center. Performing this procedure for each voxel yields the TE_{eff} map for the subject.

Once the effective echo time map is estimated, it can be accounted for during estimation of BOLD sensitivity map [24]. As shown in equation (2), the normalized BOLD sensitivity signal was calculated depending on TE_{eff} for each voxel:

$$BOLD_{TEeff} = \frac{\exp(-TE_{eff} / T2^*_{Act}) - \exp(-TE_{eff} / T2^*_{Base})}{BOLD_{TE}} \quad (2)$$

where TE_{eff} is effective echo time map; $T2^*_{Base}$ and $T2^*_{Act}$ are $T2^*$ relaxation times in baseline and active status, respectively. We use $T2^*$ time of 40 ms as baseline status, and a 10% increase in $T2^*$ as the activation signal. $BOLD_{TE}$ and $BOLD_{TEeff}$ are the BOLD sensitivity signal based on the original echo time (TE), and estimated effective echo time (TE_{eff}), respectively (Note: all BOLD sensitivity signals in this paper are normalized by $BOLD_{TE}$).

The results of estimated effective echo time and BOLD sensitivity map are spatially-variant and subject-dependent according to the calculation. Therefore, it is important to account for susceptibility gradients for accuracy of BOLD sensitivity signal when using spiral-in trajectory in fMRI.

IV. Results

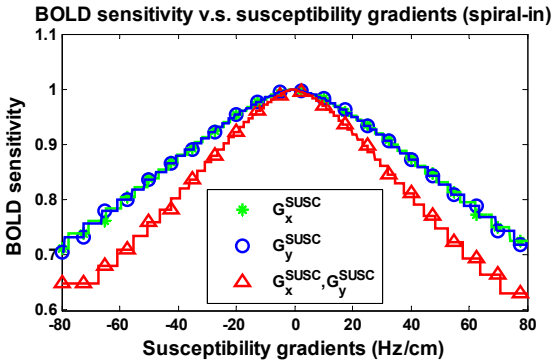


Fig. 4. The estimated BOLD sensitivity signal from effective echo time shift due to a linear susceptibility gradient using spiral-in trajectory. The green line with star and blue line with circle represent the BOLD sensitivity signal due to linear susceptibility gradients in X-direction and Y-direction, respectively; red line with triangle represents the BOLD sensitivity signal due to linear susceptibility gradients in both X- and Y-directions.

The results will be shown in this section using spiral-in trajectory. Estimated BOLD sensitivity signal from effective echo time shift due to a linear susceptibility gradient is shown in Fig.4. It shows the BOLD sensitivity signal changes induced by susceptibility gradients in X-direction, Y-direction, and both X- and Y- directions. From Fig. 4 we can see that the BOLD sensitivity values have been significantly influenced by susceptibility gradients in both X- and Y-directions in spiral-in acquisition.

For spiral-in acquisition, there are no regions across this susceptibility range that the k-space trajectory has been shifted so far that the center of k-space is not sampled. Fig. 4 shows reductions in BOLD sensitivity across the range of susceptibility gradients, but no complete loss of signal. This means that for functional imaging, even if the BOLD sensitivity has been significantly reduced, the spiral-in image will still potentially show good image intensity. This can result in a difficult-to-detect artifact in the functional image – a loss of BOLD sensitivity without a loss of signal in the image. Therefore, in this case, the functional contrast signal is not reliable in these regions in experiments of BOLD fMRI. This results in a crucial problem when assessing the accuracy of BOLD sensitivity signal in fMRI, especially in the area of the orbitofrontal cortex and temporal lobe in human brain.

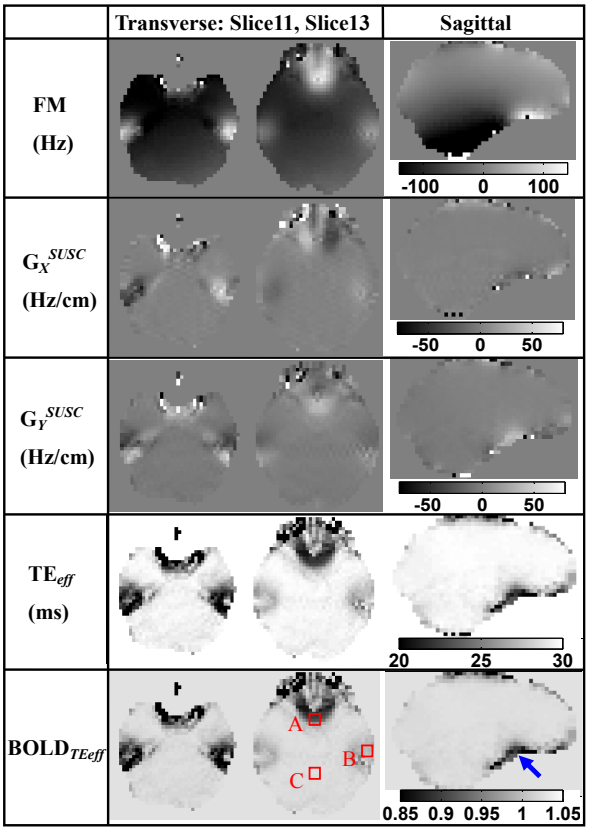


Fig. 5. Estimated BOLD sensitivity map from effective echo time map due to both X- and Y- linear susceptibility gradients maps.

As mentioned above, the BOLD sensitivity will be spatially-dependent for each voxel due to linear susceptibility gradients. Fig. 5 shows the field map (FM) and its linear gradients in X- (G_X^{SUSC}) and Y- direction (G_Y^{SUSC}) of a human subject, the estimated effective echo time map (TE_{eff}) and BOLD sensitivity map ($BOLD_{TEeff}$) induced by both G_Y^{SUSC} and G_X^{SUSC} using spiral-in trajectory. Two slices (slice 11, slice 13 of 20) in transverse plane and one slice in sagittal plane are shown across columns. As indicated by the arrow,

$BOLD_{TEeff}$ has been changed across the brain, especially severely in some areas such as orbitofrontal cortex.

TABLE I
BOLD sensitivity values in regions of interest

ROI	Average $BOLD_{TEeff}$ Value	Peak Deviation
A	0.8964	**0.1331**
B	0.9732	0.0374
C	0.9958	0.0070

Table I represents the averaged $BOLD_{TEeff}$ signals and their normalized peak deviations from $BOLD_{TE}$ in three regions of interest (ROI) (in slice 13 of transverse plane in Fig.5). It shows that the deviation of average $BOLD_{TEeff}$ sensitivity value can reach as high as 10% in some areas in the ventral brain, e.g. orbitofrontal cortex in ROI A. Therefore, the effect of effective echo time on BOLD sensitivity signal due to existence of high in-plane susceptibility gradients near the interface of air and tissue is not neglectable, and it should be considered during data acquisition and/or image reconstruction in BOLD functional MRI.

V. CONCLUSION

Based on the analysis above, we conclude that the existence of magnetic field inhomogeneity (including in-plane susceptibility gradients) and corresponding echo time shifts in gradient-echo acquisitions will cause artifacts effecting functional imaging contrast of BOLD sensitivity. This change in BOLD sensitivity is spatially-variant and subject- dependent, and it is mainly due to the distortions to the k-space trajectory of in-plane susceptibility gradients. Therefore, in order to compensate for these effects, the field map and its gradients measurements must be available and integrated in the MR imaging protocol (during acquisition or reconstruction). Adequate measurement and modeling of field map and its gradients features can enhance BOLD sensitivity.

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