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Technical Note

Improving the spatial resolution of magnetic resonance inverse imaging via the blipped-CAIPI acquisition scheme

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ABSTRACT

Using simultaneous acquisition from multiple channels of a radio-frequency (RF) coil array, magnetic resonance inverse imaging (InI) achieves functional MRI acquisitions at a rate of 100 ms per whole-brain volume. InI accelerates the scan by leaving out partition encoding steps and reconstructs images by solving under-determined inverse problems using RF coil sensitivity information. Hence, the correlated spatial information available in the coil array causes spatial blurring in the InI reconstruction. Here, we propose a method that employs gradient blips in the partition encoding direction during the acquisition to provide extra spatial encoding in order to better differentiate signals from different partitions. According to our simulations, this blipped-InI (bInI) method can increase the average spatial resolution by 15.1% (1.3 mm) across the whole brain and from 32.6% (4.2 mm) in subcortical regions, as compared to the InI method. In a visual fMRI experiment, we demonstrate that, compared to InI, the spatial distribution of bInI BOLD response is more consistent with that of a conventional echo-planar imaging (EPI) at the level of individual subjects. With the improved spatial resolution, especially in subcortical regions, bInI can be a useful fMRI tool for obtaining high spatiotemporal information for clinical and cognitive neuroscience studies.

Introduction

The acquisition time for whole-brain magnetic resonance imaging (MRI) data is limited by the time required to traverse the *k*-space. The data acquisition can be completed by either in a set of 2D *k*-space trajectories across slices or in a single 3D *k*-space trajectory covering the whole imaging volume. Conventional functional MRI (fMRI) (Belliveau et al., 1991) using blood-oxygen-level-dependent (BOLD) contrast (Kwong et al., 1992; Ogawa et al., 1990) is usually accomplished by the echo-planar imaging (EPI) (Mansfield, 1977). Considering the-state-of-the-art gradient slew rate and maximal strength, EPI can complete the 2D *k*-space traversal in approximately 40 ms per slice or 2 s with the whole brain coverage. The quest for higher temporal resolution in fMRI has been motivated by its potential to detect and to suppress physiological fluctuations in order to increase the sensitivity of detecting brain activity (Kruger and Glover, 2001; Lin et al., 2012). Likewise, high-speed echo-volumar image (EVI) integrated with parallel imaging could resolve the physiological signal fluctuation to increase the sensitivity in event-related fMRI (Posse et al., 2012; Witzel et al., 2011, 2008). In addition, higher temporal resolution of fMRI has been suggested to be beneficial for improving the power of detecting neuronally related timing information and connectivity among brain areas (Deshpande et al., 2010; Feinberg et al., 2010; Kayser et al., 2009; Lee et al., 2013; Lin et al., 2013; Roebroeck et al., 2005).

One approach in accelerating the fMRI data acquisition is to optimize the *k*-space trajectory and the corresponding reconstruction method. This can be achieved by using partial *k*-space sampling (Feinberg et al., 1986; McGibney et al., 1993), compressed sensing (Lustig et al., 2007), or exploiting a priori information (Tsao et al., 2001), such as key-hole imaging (Jones et al., 1993; van Vaals et al., 1993) and singular-value-decomposition MRI (Zientara et al., 1994). As the technology of radio-frequency (RF) receiver coil array advances, parallel MRI methods, which simultaneously acquire MRI data from multiple channels of RF coil array, have become a method of reducing the scanning time. Parallel MRI methods, such as the *k*-space SMASH (Sodickson and Manning, 1997) and GRAPPA (Griswold et al., 2002), or the image domain SENSE (Pruessmann et al., 1999) method, reduce the acquisition time by reducing the *k*-space traversal at a cost of reduced signal-to-noise ratio (SNR). In fMRI, parallel MRI has been successfully combined with the gradient-echo EPI to achieve accelerated acquisitions (Preibisch et al., 2003; Schmidt et al., 2005). It has also been demonstrated that incorporating static a priori information can further improve the sensitivity of fMRI (Lin et al., 2005).

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The inverse imaging (InI) method (Lin et al., 2006) is a further generalized parallel MRI method for 3D volumetric acquisition by leaving out all partition-encoding steps. Consequently, the volumetric brain is projected along the partition-encoding direction onto a single plane. InI is closely related to the MR-encephalography (Hennig et al., 2007). InI reconstructs a 3D image from a set of 2D projection images from different channels of an RF coil array using the coil sensitivity information. Mathematically, the image reconstruction is performed by solving a set of underdetermined linear systems. Combined with the echo shifting technique (Chung and Duerk, 1999), the sampling rate of whole-brain InI can become as high as 40 Hz (Chang et al., 2013). While InI allows for a very high temporal resolution, the attainable spatial resolution depends on the available spatial information in the RF coil array. Correlated coil spatial information will cause spatial blurring in the InI reconstruction. One strategy to improve the spatial resolution is through the use of a more sophisticated reconstruction algorithm, such as reconstructing the images in *k*-space (Lin et al., 2010) or using spatial filtering (Lin et al., 2008; Liou et al., 2011). Another strategy is to modify the data acquisition by collecting data from multiple projections instead of one single projection (Tsai et al., 2012).

In this study, we aim to improve the spatial resolution of InI by modifying the spatial encoding in the pulse sequence. Specifically, InI was integrated with the "blipped-CAIPI" acquisition (Setsompop et al., 2012) to create the "blipped-InI" (bInI) method. The blipped-CAIPI technique has been used in the Simultaneous MultiSlice (SMS) acquisition, which spatially shifts the aliasing patterns of simultaneously acquired slices. This is achieved by applying additional slice-selection gradient blips concurrently with the EPI phase-encoding blips. The additional slice-selection gradient blip provides additional encoding that helps differentiate signal from different slices and thereby reduces the noise amplification (*g*-factor) penalty. In this work, we applied the blipped-CAIPI acquisition concept to InI in order to reduce spatial blurring. In the following sections, we first introduced the bInI acquisition and reconstruction method. We then quantitatively characterized the spatial resolution and localization accuracy of bInI using synthetic data. Finally, we performed in vivo experiments of event-related BOLD fMRI using bInI. These BOLD responses were then compared with the BOLD responses obtained from standard EPI and InI experiments. The simulation results suggested that, compared to InI, bInI can improve the spatial resolution up to 33% and localization accuracy more than 100% in subcortical regions. Compared to InI, the fMRI experimental results using bInI showed improvement in the robustness of activation maps.

Theory

Pulse sequence of blipped InI

Without losing generality, we use *x*, *y*, and *z* axes to represent the axis along read-out, phase-encoding, and partition-encoding directions, respectively. Fig. 1(a) shows the pulse sequence diagram of the bInI, where α denotes the flip angle. This pulse sequence diagram is similar to the conventional single-slice 2D EPI acquisition, except additional partition-encoding gradient (G_z) blips and slab-selective RF pulse. These additional G_z blips are of the same patterns to the ones used in the blipped-CAIPI acquisition sequence for the Simultanous MultiSlice (SMS) acquisition (Setsompop et al., 2012). These G_z blips are in synchrony with the phase-encoding gradient (G_y) blips in order to provide extra spatial encoding along the *z* axis. Two variants of G_z blips are shown in Figs. 1a and b, which achieve in-plane shift of FOV/2 (Fig. 1a) and FOV/3 (Fig. 1b). The gradient moment of the G_z blips in the bInI pulse sequence can be expressed as

$$\beta\Delta k_z = \beta \cdot (2\pi/(\gamma \cdot FOV_z)), \tag{1}$$

where β denotes a real-number scale factor, γ denotes the gyromagnetic ratio, and FOV_z denotes the length along partition encoding direction. Δk_z is the minimum spacing in *k*-space along the k_z direction.

For the SMS acquisition, the G_z blip encoding creates an inter-slice image shift along the phase encoding (PE) direction between simultaneously excited slices (Breuer et al., 2005; Lee et al., 1995; Setsompop et al., 2012). The effect of this blip encoding on volumetric bInI is different from the multi-slice acquisition. Fig. 2 shows the principle of bInI encoding for the case of in-plane FOV/2 shift and $|\beta|$ of 1. The red dashed lines in the left-most image in Fig. 2a delineate image partitions (obtained after all partition encoding steps). Since G_z blips always have zero gradient moments in odd phase encoding lines, the G_z blips only introduce phases in even phase encoding lines. Moreover, different phase offsets are introduced by the G_z blips in the even *k*-space lines for different partitions. Considering the case that the partition s2 is at the scanner iso-center and thus has no phase offset. On the contrary, G_z blips introduce $-\pi/4$ and $\pi/4$ at partitions s1 and s3 respectively, which are at the position 3/8 and 5/8 of the FOV in the partition encoding direction. These phase modulations on different phase encoding lines of the different partitions are marked at the right margin of s1, s2, and s3 panels in Fig. 2a. In the image space, these *k*-space phase modulations cause spatial shifts of FOV/2 along the phase encoding direction for all partitions but with different weighting for different partitions, as shown in Fig. 2b. The top row in Fig. 2b shows the images in representative partitions without the phase modulation introduced by G_z blips. The middle row shows the phase offsets introduced by G_z blips. The modulated slice images are shown in the bottom row. Using such G_z blips, strong *N*/2 ghost is observed in the partitions toward the edge of the excitation volume, while central slices show relatively weak *N*/2 ghost. In accelerated bInI acquisition, all the partition encoding steps are removed and consequently all the partitions are integrated, as shown in the right-most images in Fig. 2b. Note that the similar analysis principal can be applied to other type of shifts such as FOV/3.

As the SMS method can be formulated as a 3D encoding framework (Zahneisen et al., 2013), the concept of bInI can be understood in 3D k-space as well. Fig. 3 shows the k-space trajectories of InI and blipped

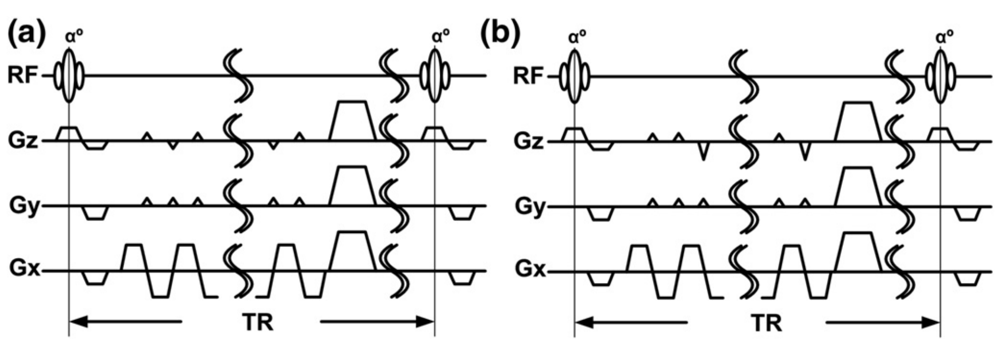

Fig. 1. The blipped-InI pulse sequences to achieve (a) FOV/2 and (b) FOV/3 in-plane shifts. In (a), the G_z blips change the polarity alternatively between read-outs but have the same magnitude of gradient moment. Such G_z blips can induce FOV/2 in-plane shift. In (b), the G_z blips have the repetitive "up–up–down" pattern across read-outs. The downward G_z blips have twice the gradient moment of the upward G_z blips. Such G_z blips can introduce FOV/3 in-plane shift.