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Technical Note

Single shot partial dual echo (SPADE) EPI—an efficient acquisition scheme for reducing susceptibility artefacts in fMRI

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ABSTRACT

SPADE is a new acquisition scheme for fMRI based on dual echo EPI. As in previous work, additional spin echo EPI images are used to recover signal in regions that are affected by susceptibility related sensitivity loss in gradient echo EPI. However, with SPADE the additional spin echo images are only acquired for the affected slices, which reduces the acquisition time and enhances the time normalised signal-to-noise ratio. We demonstrate the feasibility of this approach and discuss potential applications of the SPADE technique in fMRI. We conclude that SPADE provides an efficient acquisition scheme for fMRI applications where whole brain coverage and sensitivity is required.

Introduction

FMRI studies of the orbitofrontal cortex or the inferior frontal lobes are often compromised by susceptibility artefacts, which may result in signal reduction or loss in gradient echo (GE) EPI (Deichmann et al., 2002). Spin echo (SE) EPI is considerably more robust regarding susceptibility-related signal loss, but its intrinsic sensitivity to changes in the blood oxygenation level dependent (BOLD) contrast is generally lower (Norris, 2006). As recently demonstrated, dual echo EPI, in which both a GE and an SE image are acquired at each slice position, provides an attractive solution for fMRI studies that require optimum sensitivity in all brain regions (Schwarzbauer et al., 2010). This approach benefits from the robustness of SE EPI in regions that are affected by susceptibility artefacts, whilst utilising the generally higher sensitivity of GE EPI in other regions of the brain. Spatial and temporal misregistration between the GE and SE image are negligible, as both images are acquired following a single slice-selective excitation. However, for many fMRI applications, the acquisition scheme is suboptimal for a number of reasons. Firstly, the minimum repetition time (TR) is more than 100% longer than a standard fMRI sequence based on GE EPI, due to the time required for the additional SE image at each slice position. The resulting temporal resolution may therefore be insufficient for event-related fMRI designs, particularly if whole brain coverage is required. Secondly, the acquisition scheme is inefficient because susceptibility artefacts typically occur in the lower third of the brain, but the additional SE images are acquired at all slice positions. The time required for these unnecessary SE images results in a sub-optimal time normalised signal-to-noise ratio (SNR). Thirdly, the 180° refocusing pulses lead to a substantial increase in the specific absorption rate (SAR), which may be particularly problematic at higher field strengths.

In this article, we address these issues using an enhanced acquisition scheme, in which additional SE images are only acquired where necessary, i.e. at slice positions that are affected by susceptibility artefacts (Fig. 1a). We refer to this acquisition scheme as single shot partial dual echo (SPADE) imaging.

Methods

Data acquisition

The SPADE acquisition scheme is illustrated in Fig. 1b. Following a non-selective 90° fat suppression pulse and a slice-selective 90° excitation pulse, a GE EPI image is acquired. A slice-selective 180° refocusing pulse is then applied to reverse the temporal evolution of the transverse magnetisation, and an SE EPI image is acquired with the spin echo occurring at the centre of k-space. The SE EPI image is only acquired for slices that are affected by magnetic field inhomogeneities (see Fig. 1a).

The SPADE technique was implemented on a 3T whole body scanner (Siemens MAGNETOM Trio), using a modified EPI pulse sequence and image reconstruction program. Thirty-two transverse-oblique slices were acquired to cover the whole brain with a slice thickness of 3.0 mm and an inter-slice gap of 1.0 mm. Additional SE images were only acquired for the lower 12 slices. The GE and SE echo times were $TE_{GE} = 30$ ms and $TE_{SE} = 100$ ms, respectively. The matrix

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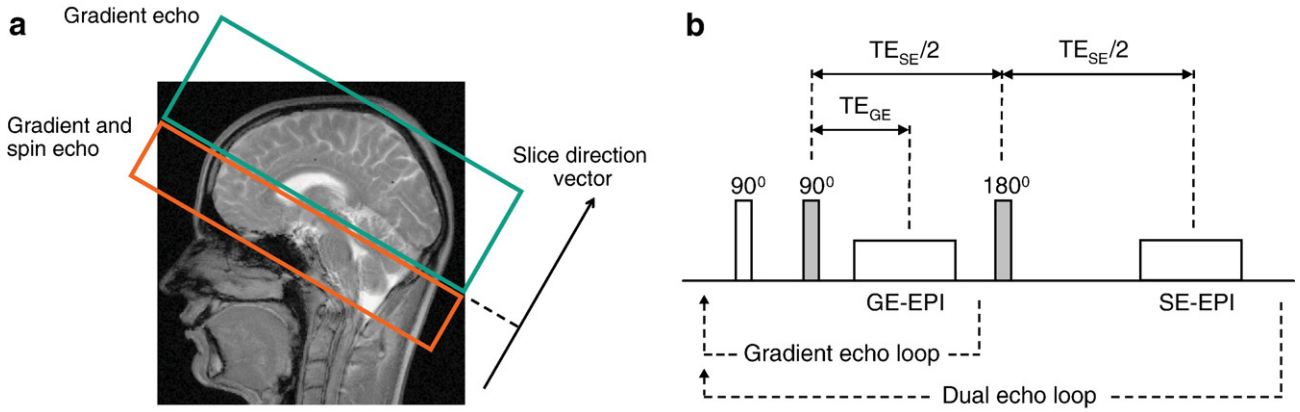

Fig. 1. Illustration of the SPADE principle. (a) Acquisition scheme. Additional spin echo EPI images are only acquired for slices affected by susceptibility artefacts. These are typically located in the lower part of the brain. (b) Pulse sequence consisting of a non-selective 90° fat suppression pulse and a slice-selective 90° excitation pulse. Following the acquisition of a GE EPI image, a slice-selective 180° refocusing pulse is applied and an SE EPI image is acquired such that the spin echo is positioned at the centre of k-space.

size was 64×64; field of view, 192×192 mm^2; in-plane resolution, 3×3 mm^2. A total of 50 SPADE EPI volumes were acquired for each subject using a repetition time (TR) of 2.9 s per volume.

High-resolution structural images were acquired using an MP-RAGE sequence (Mugler and Brookeman, 1990) with echo time, 2.99 ms; repetition time, 2250 ms; inversion time, 900 ms; flip angle, 9°; matrix size, 256×240×160; field of view, 256×240×160 mm^3; voxel size, 1×1×1 mm^3; and with GRAPPA parallel imaging (Griswold et al., 2002) using an acceleration factor of 2.

Four healthy adult volunteers participated in the study. All subjects gave written informed consent after the nature of the study and its possible consequences were explained to them. The study was approved by the Cambridgeshire Local Research Ethics Committee.

Data analysis

All data were analysed using Statistical Parametric Mapping software (SPM2, Wellcome Department of Imaging Neuroscience, London). The structural MP-RAGE image was skull-stripped and coregistered to the mean image of the GE EPI volumes. The normalisation (inter-subject registration) parameters were calculated to match the coregistered structural images to a skull-stripped version of the standard Montreal Neurological Institute (MNI) 152 T1 average brain. The resulting transformation was applied to both the GE and SE volumes and the data were resliced to 3×3×3 mm^3 voxels in MNI space. Spatial smoothing was performed using an 8-mm FWHM Gaussian kernel.

Field map database and calculation of G_s

The FIELDMAP 932 database has recently been established at the MRC Cognition and Brain Sciences Unit, Cambridge, UK. It consists of 932 individual field maps that were acquired during standard fMRI studies on healthy volunteers (462 male, 470 female; age median, 25 years; age range, 18–75 years). The original data (2D structural and phase difference images) were acquired on a 3T scanner (Siemens Magnetom Tim TRIO) using a standard double echo GE sequence: TE_1/TE_2 = 5.19 / 7.65 ms; TR = 400 ms; flip angle = 60°, slice thickness = 3 mm; matrix size = 64×64; in-plane resolution = 3×3 mm^2; total acquisition time = 54 s. The phase difference images were unwrapped and converted into magnetic field maps (Jenkinson, 2003). Maps of the magnetic field gradient modulus were calculated according to $G = |\nabla B_0|$, and transformed into the MNI standard space using the corresponding structural images to derive the transformation matrix as described in the previous section. A map of the average susceptibility gradient modulus, G_S, was calculated by averaging the normalised individual gradient maps.

Results and discussion

Fig. 2 shows a representative image volume acquired with the SPADE technique. In the GE EPI images, typical signal voids are visible in regions where there are macroscopic magnetic field inhomogeneities due to the susceptibility difference between brain tissue and air in nearby sinuses. Regions affected include the orbitofrontal cortex, as well as parts of the temporal lobes and the lateral cerebellum. The corresponding SE EPI images demonstrate a recovery of the signal loss in these regions because the spin echo eliminates the static phase dispersion caused by macroscopic magnetic field inhomogeneities.

Magnetic field inhomogeneities typically only affect the lower third of the brain as illustrated in Fig. 3. By restricting the acquisition of additional SE images to this region, SPADE provides a more efficient acquisition scheme than the conventional single-shot dual echo approach. Using the SPADE technique, whole brain coverage was possible at a repetition time of 2.9 s compared to 4.4 s if an SE image had been acquired at all slice positions. This makes SPADE suitable for event-related fMRI designs, for which a high temporal resolution is essential. The time normalised SNR, $TSNR = SNR / \sqrt{TR}$ is greatly improved by restricting the additional SE acquisitions to slices with susceptibility artefacts. It was found that 12 slices were sufficient to cover such critical areas when using a slice thickness of 3 mm and an inter-slice gap of 1 mm. This corresponds to an improvement in the TSNR of 23% compared to conventional dual echo EPI. There is also a reduced number of RF refocusing pulses per unit time, which results in a significantly lower SAR and makes SPADE particularly attractive for MRI at high and ultrahigh field strengths.

In SPADE, GE and SE images are acquired following a single excitation pulse. The delay between the GE and SE image, which is given by the difference in the echo times ($T_{SE} - T_{GE} = 70$ ms), is negligible compared to the temporal characteristics of the haemodynamic response. The short interval between the two acquisitions also prevents any spatial misregistration due to subject movement. Image distortions related to magnetic field inhomogeneity are the same in the GE and SE EPI, as the corresponding EPI readout modules are identical.

In most fMRI studies, a spatial realignment algorithm is used to correct for subject movement. In addition, individual fMRI data sets are often transformed into a standard coordinate system, such as Tarailach or MNI space. In SPADE, SE data are typically only acquired for the lower part of the brain (see Fig. 1a). We therefore recommend to obtain the corresponding transformation parameters from the GE