Echo Volumar Imaging (EVI) for high temporal resolution fMRI

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Introduction

Even though EVI (1) offers an excellent way of acquiring volumar data at high speed, the method has not been widely used for fMRI studies (2). This is a consequence of the heavy demands that the encoding of 3-dimensional information after a single excitation imposes on the gradient hardware, and problems arising from the long echo trains that are generally therefore employed. The latter include: (i) a long effective echo time, which may limit BOLD sensitivity; (ii) significant Nyquist ghosting due to mismatch of data in successively acquired planes of k-space; (iii) a high degree of field-inhomogeneity-induced image distortion resulting from the low frequency per point in the slowest sampled direction. Here, we describe a number of modifications to the EVI sequence that alleviate these problems, and the application of this approach to fMRI studies of somatosensory cortex with a high rate of volumar data acquisition (*TR* = 167 ms).

Methods

Technique The modified EVI sequence, in which data in N_z planes of k-space each made up of N_x echoes containing N_y data points are sampled and used to produce an image of $N_x \times N_y \times N_z$ matrix size, is shown in Fig. 1. In the original EVI sequence (1) the sign of the rapidly blipped, x-gradient is reversed in successively acquired k_x-k_y planes. After data reversal this results in phase evolution due to field inhomogeneites occurring in opposite senses in alternate planes, thus giving rise to a Nyquist ghost which occurs in the slowly sampled z-direction in regions of field inhomogeneity. In the modified sequence, a 'rewind-gradient' is played out simultaneously with the gradient pulse in the slice-select direction so that all k-space planes are sampled using the same polarity of x-gradient. This removes the Nyquist ghost and also simplifies data reordering before Fourier transformation.

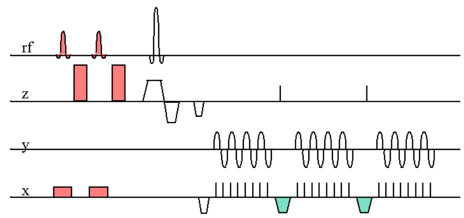

Figure 1. EVI Pulse sequence with zoom-pulses (red) played out along the z -axis. Rewind gradients (green) are applied along x, simultaneous with the gradient pulses along z.

The duration of the echo train in Fig. 1 is $T_{EC} = (N_x\tau + T_{RW}) \times N_z$, where τ is the duration of each echo under the switched y-gradient, while T_{RW} is the length of the rewind gradient. The minimum effective echo time is $TE = T_{EC}/2 + T_{SL}$, where T_{SL} is the duration of the slice selection module. The spatial distortion in the z-direction due to a frequency offset $\delta\omega$ is proportional to $\delta\omega T_{EC}$, so it can be seen that achieving an acceptable echo time and level of spatial distortion requires limitation of the number of echoes sampled ($N_x \times N_z$) and/or the time per echo. Here, a high gradient switching frequency of 1.9 kHz (τ = 260μs) was used and only 256 echoes (N_x=32, N_z=8) acquired per acquisition using T_{RW} = 1.04 ms. This gives T_{EC} = 75 ms, TE = 44 ms, and a frequency per point in the z-direction of 13 Hz. A physiologically relevant spatial resolution was achieved within the small matrix by using a surface coil and zoomed imaging techniques to limit the field of view (FOV), while avoiding wrap-around artefacts. Two double-slice selective zoom-pulses, each followed by spoiler gradient pulses, were applied before each z-slice selective pulse to prevent aliasing of signal from outside the FOV in the x- direction.

Interleaved imaging approaches in which data from alternate k_x lines or k_x-k_y planes are acquired from two separate excitations (with appropriate echo-time shifting) have also been evaluated. The interleaved approach has the benefit of reducing T_{EC} by a factor of two, although temporal resolution is compromised.

The calibration scan method, commonly used in EPI (3), was adapted for use with EVI so as to reduce Nyquist ghosting and image distortion further. This involved acquisition of a calibration data set without applying a blipped gradient in the z-direction. The Fourier transformation of this data with respect to k_x and k_y yields a set of N_z images that can be used to form maps showing the average phase evolution, ϕ_n(x,y) within the excited z-slab at times nT_{EC}/N_z. Phase correcting data acquired with z-gradient pulses by subtracting ϕ_n(x,y) prior to Fourier transformation with respect to k_z removes phase mismatches between alternate planes and eliminates the distortion due to the average field offset across the slab. Distortion due to field variation with z-position remains.

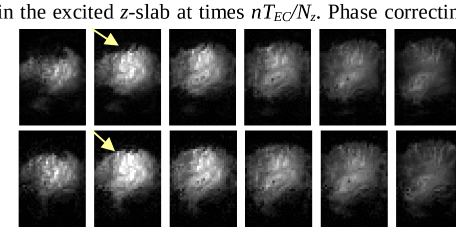

Figure 2. Correction of brain image using the reference scan method. Top row slices before, bottom row after correction.

fMRI Studies Three subjects were scanned on a 3T scanner using a 27-cm diameter, TEM volume excitation coil and a 4-cm diameter receiver-only surface coil, placed over the somatosensory cortex. Non-interleaved fMRI data were acquired with a resolution of 3-mm in plane and 1.5 mm in the slice-select direction and a matrix size of 64x32x8. Six volumes, comprising 8 sagittal slices, were sampled per second (*TR*=167 ms). Two activation paradigms involving vibrotactile stimulation of the thumb were employed: (i) a block paradigm consisting of 12 cycles each of 30 s duration with a 6 s on period; (ii) a discrimination task in which, stimuli of 2 s duration were presented in pairs with a 10 s gap, followed by a 26s off-period over 10 repetitions. The 1st stimulus was always applied at 20 Hz, whilst the 2nd occurred at either 20 or 35 Hz. Subjects were asked to discriminate the two stimuli in a pair.

Results and Discussion

Using the modified sequence and small RF coil, volumar data with a good SNR and no significant Nyquist ghost could be acquired at a rate of 6 volumes per second. The modified calibration-scan method was found to significantly reduce distortions as demonstrated by Fig. 2, which shows the relocation of signal to the correct slice (see arrow in fig. 2) in brain image data after phase-correction.

A comparison of images obtained by interleaving data from two separate excitations, indicates that interleaving alternate k_x lines yields better image quality, because when interleaving data from alternate k_x-k_y planes the artefact due to signal differences in interleaves always overlaps the signal from other slices. In future the use of navigator echoes should reduce this effect and make interleaved EVI suitable for functional studies.

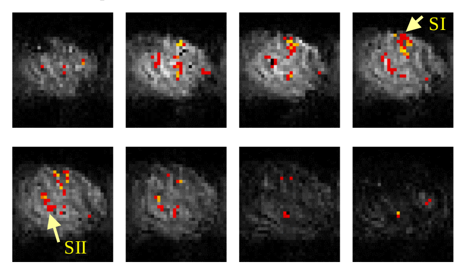

Figure 3. Activation map for a block paradigm test overlaid on the slices of a volumar image (P_{corr} = 0.01).

A functional map (p_{corr}= 0.01) generated from 8 sagittal slices spanning 1.2 cm using paradigm (i) is shown overlaid on EVI data in Fig. 3. The spatial resolution and contrast are sufficient to distinguish grey and white matter and allow identification of the Silvian fissure and central sulcus. Active areas are found in SI and SII, as shown by the arrows. The average time course of a group of active voxels found in SII in a representative subject during the frequency discrimination experiment is shown in Fig. 4. Both haemodynamic responses are well defined with a temporal resolution of 167 ms. Analysis is now focussing on measuring timing differences (4) between responses occurring when the 2nd stimulus has the same, or a different frequency to the 1st.

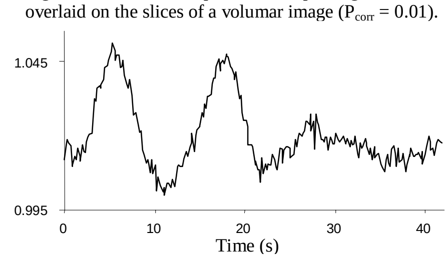

Figure 4. Time course of a group of active voxels in SII from a decision-task data set.

References (1). P. Mansfield et al, 1995, J Comput Assist Tomogr. 19:847-52; (2) H. Bruder *et. al.*, 1992, Magn. Reson. Med. 23:311-323; (3) Y. Yang *et al.* , 1997, JMRI, 7:371-375; (4). L.C. Liu *et al.*, 2003, Neuroscience, 121: 141-154

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