Curved Slice Functional Imaging

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Introduction As demonstrated previously [1], the ExLoc concept allows excitation and geometrically matched spatial encoding of curved slices by the application of a set of nonlinear, but locally orthogonal, encoding fields (Fig. 1) in combination with conventional RF-pulses. As the encoding fields are based on an adjustable superposition of spatially linear and nonlinear varying magnetic field components, encoding-field shape and thus curvature, orientation and position of the slices can be chosen with high flexibility. This allows a better adaptation of the slice geometry to the anatomy under investigation and thus a more efficient exploitation of the relevant diagnostic information.

In particular for functional MRI experiments, further benefits may be expected: ExLoc would not only allow an increased sampling rate of the BOLD signal by more efficient coverage, but also separate loci activation could be simultaneously selected for synchronized data acquisition. In this study, the ExLoc concept is applied to echo planar imaging (EPI). Alongside the implementation and analysis of the image quality, we also present preliminary results from a curved slice fMRI experiment.

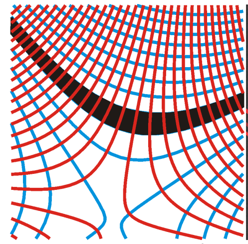

Fig. 1: Isocontours of an ExLoc slice selection field (blue), the corresponding encoding field (red) and a cross-section of the selected slice (black).

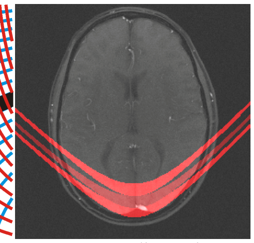

Fig. 2: Localizer image with the cross sections of the selected slices.

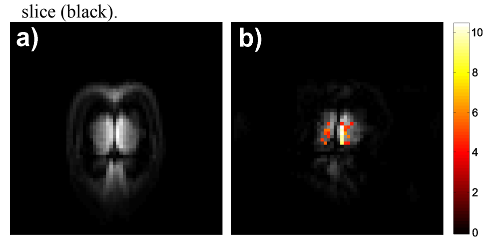

Fig. 3: Curved slice GE image (a) and curved slice echo planar image (b) with activation map of the bottom slice in encoding space with same resolution and FOV. The phase encoded curved dimension points from left to right.

Methods

Data acquisition was performed on a 3T MAGNETOM Trio Tim system (Siemens, Erlangen, Germany) equipped with a PatLoc gradient insert [2]. The five available magnetic field components (x, y, z, 2xy, x^2-y^2) offer encoding fields for slices with one curved dimension lying in the xy plane. For application of an in-house developed gradient echo sequence with a single shot EPI readout, all three logical gradient channels had to be mapped to the correct combinations of the physical field components. The phase encoding direction was assigned to the curved slice dimension, the read direction oriented along the z-axis. A 64 × 64 k-space was acquired without undersampling using an 8 channel head array. Reconstruction of the curved slice EPI data was performed in Matlab (The MathWorks, Natick, USA) in a two-step process: For transformation into the distorted encoding space [3], a regularized nonuniform fast Fourier transform was applied [4,5]. Subsequent transformation into the undistorted object space followed on the basis of an analytical description of the encoding fields.

For functional imaging, a curved slice was adjusted to the visual cortex of a healthy volunteer after ethics approval. During EPI data acquisition (matrix: 64 × 64, FOV: 26.6 × 21.0 cm, max slice thickness: 10.7 mm, TR: 1000 ms, TE: 4 ms, FA: 90°, dwell time: 5 µs, 192 frames, total duration: 3 min, 12 sec) the visual stimulation was achieved by illumination of the darkened magnet room using a block design (15 sec dark, 15 sec flashing light with 8 Hz rate). Statistical analysis of the fMRI data without spatial smoothing was performed in encoding space using SPM8 (www.fil.ion.ucl.ac.uk/spm). The resulting t-maps were transferred into the object space as described above and overlaid with an echo planar image. The experiment was repeated for three different slice positions as shown in Fig. 2. For reference higher resolution gradient echo (GE) images (matrix: 256 × 256; TR: 100 ms, TE: 20 ms, FA: 15°) were acquired with the same curved geometry.

Results

Fig. 3 shows an echo planar image overlaid with the resulting activation map (b) and a GE reference image with matched resolution (a) of the bottom slice. Both images are displayed in encoding space for better demonstration of the native image quality. The intensity variation from left to right results from the nonlinearity of the encoding field applied for phase encoding. The echo planar image reveals an image quality comparable to the GE image within the brain, whereas the scalp is less visible, as is typical for EPI. Activation of the visual cortex is clearly visible ($t_{threshold}$ = 4.10). The final echo planar image in object space is displayed beside the high resolved GE reference image in Fig. 4 (a & b). Distortions in the echo planar image are amplified during coordinate transformation and uncorrected N/2 ghosting is enhanced towards the FOV periphery by the intensity correction. However, the underlying anatomy is clearly distinguishable. The results for the two remaining slices (Fig. 4 c-d) exhibit comparable quality. As the separation of the hemispheres is no longer resolved, the activation patterns on both sides appear connected.

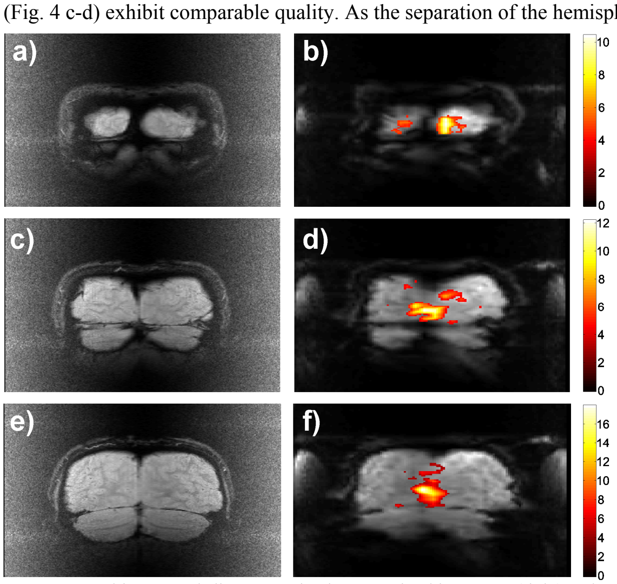

Fig. 4: Resulting curved slice EPI activation maps in object space (right) and high resolved GE reference images (left) for the bottom (a, b), center (c, d) and top slice (e,f). As the separation of both hemispheres is no longer resolved, the activation patterns on both sides appear connected in the center and the top slice.

Discussion

This study demonstrates the feasibility of curved slice functional MRI using the ExLoc concept. The resulting echo planar images reveal suitable quality and allow observation of the BOLD signal. Using conventional linear gradients only, demonstration of activation maps in such a curved coordinate system would require 3D imaging and complex reformatting. Although the variety of usable slice shapes in this study is limited by the small number of available field components, it is expected to increase with upcoming higher order gradient systems such as [6]. Inhomogeneities of the B_0 field are expected to be the main source of distortions within the presented echo planar images. Due to the linear behavior of the encoding space, standard B_0 distortion correction methods such as [7] can be applied within the first step of the image reconstruction. Single-shot acquisitions are particularly sensitive to trajectory deviations resulting from effects such as eddy currents, small timing imperfections, or concomitant fields. In this work we were able to obtain high quality images even without calibrating for such effects by applying the nonlinear field in the 'slow' phase-encoding direction. We expect that methods such as magnetic field monitoring [8] would provide a method to perform this calibration and allow for even more flexible encoding. The nonlinearity of the encoding field applied for slice selection results in slice-thickness reduction up to 50 % towards the periphery of the object. Although this variation seems to be acceptable for functional imaging, the thickness variation results in gaps between the slices of the single experiments (see Fig. 2). In future work, the presented imaging technique will be extended for multi-slice imaging in order to achieve object coverage without gaps.

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References [1] Weber et al., Proc. ISMRM 2011, #2806; [2] Welz et al., Proc. ESMRMB 2009, #316; [3] Schultz et al., MRM 2010, 64:1390; [4] Zahneisen et al., MRM 2011, 65:1260; [4] Grotz et al., MRM 2009, 62:394; [5] Littin et al., Proc ISMRM 2011, #1837; [6] Jezzard et al., MRM 1995, 34:65; [7] Wilm et al., MRM 2011, 65:1690;