Real-Time Prospective Slice-by-Slice Motion Correction for fMRI in Freely Moving Subjects

O. Speck[1], M. Zaitsev[1]
[1]Dept. of Diagnostic Radiology, Medical Physics, University Hospital Freiburg, Freiburg, Germany

INTRODUCTION

Functional Magnetic Resonance Imaging (fMRI) is being used extensively in neuroscientific studies and is entering the clinical field. Due to its low inherent effect to noise ratio even at high field strength the results are often compromised by adverse events during the acquisition. The most frequent cause of signal fluctuations that degrade the detection of paradigm induced neuronal activation is subject motion. A number of methods have been proposed to cope with motion. Most of the established methods correct motion based on the acquired imaging volumes either retrospectively [1] or prospectively [2]. They don't require changes in the acquisition but can only correct for motion between successive volume acquisitions. Navigator based motion correction has been demonstrated [3]. However, it introduces additional disturbance of the spin system and requires extra scan time.
We have developed and introduced a prospective motion correction method based on optical tracking of the object motion with unprecedented spatial and temporal accuracy [4]. The method adapts the position of each slice to follow the motion of the subject in real time. The goal of this study was to apply this method to fMRI measurements and compare it to image based retrospective and prospective motion correction methods.

MATERIALS AND METHODS

The optical tracking system (ART, Weilheim, Germany) was interfaced with the scanner's control unit. Adaptation of the slice position and angle was performed with an update rate of up to 60 Hz and a delay of only 30 ms in the complete measurement chain. A newly developed cross calibration procedure reduced the calibration error to below 0.1 mm and 0.1 degree. The experiments were performed on a 3T system (Siemens Magnetom Trio) using a modified EPI sequence that adapts the imaging volume to the subject motion prospectively either slice-by-slice based on the optical tracking data, or volume-by-volume based on the imaging data (PACE). In addition, a standard EPI measurement with retrospective motion correction was used. All methods used identical MR-parameters (TR 3000ms, TE 30ms, matrix 64*64, 40 slices, isotropic resolution of 3mm). During each fMRI run, 70 repetitions were acquired with visual stimulation in a block design (circular checker board; 30s off, 30s on). All three variants were repeated without intentional motion and with the subjects being instructed to move reproducibly with either slow or fast motion. This resulted in 9 experimental runs and 12 data sets (prospective optical, prospective image based, retrospective image based, and uncorrected).
All data sets were processed with SPM2. After smoothing with a 6mm Gaussian kernel voxel exceeding a statistical threshold of $p=0.05$ (FWE) were considered to be activated. From the datasets without motion, a mask of activated voxel was generated including only voxel within the occipital lobe and on the optic pathway (including LGN). This mask was extended by region growing and considered truly activated. The number of activated voxel, activated voxel within the optical areas as well as the rate of false positive and false negative activations was calculated for each experiment.

RESULTS

Subject motion within the three conditions was comparable. Motion amplitudes were large and approx. 20-30° for slow and fast motion with the repetitive motion occurring during 8-10s for slow and during 1-2s for fast motion. Examples of EPI images and activation maps are shown in Fig. 1 and 2. The results of a quantitative evaluation of sensitivity and specificity are shown in Fig. 3.

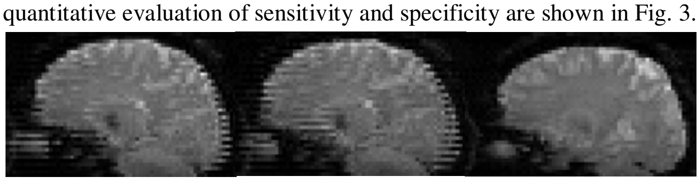

Fig. 1: Sagitally reformatted axially acquired EPI data after retrospective (left) and prospective (middle) image based motion correction and with prospective optical slice-by-slice correction (right).

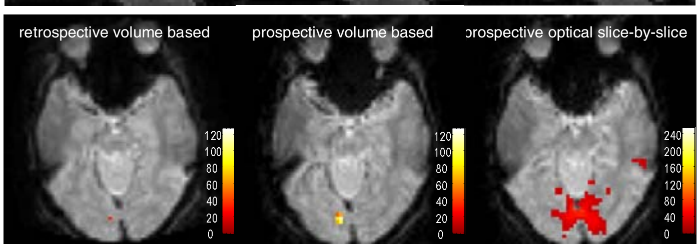

Fig. 2: fMRI activation maps calculated from the data with slow but large amplitude motion (20-30° rotation within 10 s) during the scan. Only the prospective optical motion correction can recover most of the activation. Note that the color scale is increased by a factor of two for the first two images.

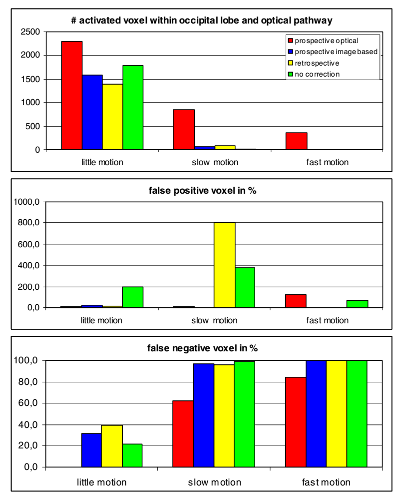

Fig. 3: Quantitative evaluation of the number of activated voxel.

DISCUSSION

This study demonstrates that prospective slice-by-slice motion correction by means of optical detection is superior to either prospective or retrospective image-based correction for fMRI application. Especially in cases where significant motion occurs during the acquisition of a single volume, only prospective slice-by-slice correction can recover the correct object geometry. With this short scanning protocol of only 3.5 minutes, small structures, e.g. the LGN, have only been detected with our new optically detected prospective motion correction. Thus, using the proposed prospective correction allows fMRI even in the case of excessive motion, e.g. in compromised patients. This also reduces the demands on uncomfortable subject restraints significantly. fMRI of freely moving subjects seems to be possible. However, even with perfect prospective correction of subject motion, the scan sensitivity is significantly reduced for large scale motion. This is most likely caused by changes in the local magnetic field distribution and thus corresponding signal fluctuations that can mask the activation induced signal change.

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