Real-Time Intra-Volume Motion Correction in EPI Using Active Markers

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Introduction: Echo-planar imaging (EPI) is the sequence of choice for functional MRI (fMRI), where rapid scanning is needed in order to continuously acquire complete brain volumes for a time-series analysis. Even a few millimeters of movement during an fMRI scan can result in large, artifactual, signal changes in the time-series data that will obscure the relatively small brain activation signals, leading to false positives in the subsequent statistical analysis. To compensate for motion, fMRI studies almost exclusively employ retrospective image-based methods to estimate the six degrees of freedom (6-DOF) rigid-body head motion (three rotations θ_x, θ_y, θ_z and three translations t_x, t_y, t_z, about an orthogonal coordinate system), and to co-register each brain volume in the time-series.

However, retrospective correction involves interpolation, which can cause image blurring, and is unable to fully correct for the influences of through-plane motion on local spin-history (1,2); additionally, the most common algorithms (3) only corrected for inter-volume motion (between dynamics), neglecting potential intra-volume motion between slices in the same dynamic. To avoid these limitations, several prospective strategies for EPI have been proposed – including image-based methods (2), 3D-navigators (1,4,5), and optical markers (6) – that compensate for motion in the acquisition stage by keeping the image-plane at a fixed orientation relative to the head during the scan. Here, we present the use of micro RF-coil "active markers" for real-time motion tracking (7-9).

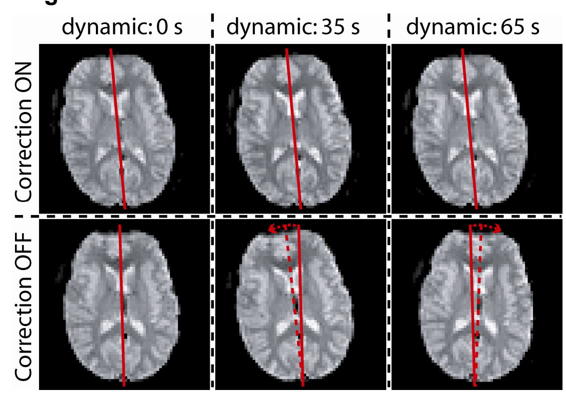
The improvement in image quality achieved using active markers for real-time motion correction has already been established for structural brain imaging (10,11). The current work demonstrates the first use of active markers for intra-volume (slice-by-slice) prospective motion correction in 2D-EPI sequences.

Methods: Experiments were performed on a 1.5T Philips Achieva (Philips Medical Systems, Best, The Netherlands). A headband integrated with three active markers is securely affixed to the volunteer's forehead so that any head movement is reflected in the markers. A short tracking pulse-sequence, consisting of 1D projection readouts in three orthogonal directions, is used to measure the 3D-positions of the active markers before the acquisition of each EPI-slice. From this tracking data, the 6-DOF rigid-body transform is calculated that realigns the current active marker positions to their initial (reference) locations; the transform is then fed back to prospectively update the image-plane for rotational and translational head motion before the next EPI-slice is acquired. In cases of extreme/abrupt motion, corrupted slices are rejected and reacquired with the updated geometry. For a detailed presentation of the active marker design, tracking pulse-sequence, and correction calculations, please refer to ref. (11).

The multi-channel MR system allows simultaneous imaging using a standard bird-cage coil, and position tracking with our active marker headband. Slice-by-slice prospective correction was applied to a single-shot 2D-EPI dynamic scan (TE/TR = 40/1350 ms, θ = 85º, FOV = 192×192 mm, voxel size = 3×3 mm, thickness/gap = 5/1 mm, slices = 20, dynamics = 10). Scans were performed on a volunteer trained to reproduce two types of motion throughout the entire scan: an abrupt-intermittent left-right head-jerk, and a smooth-continuous left-right head-shake. For each motion, two scans were acquired – with correction ON and OFF – in order to evaluate improvements in image quality under similar motion conditions. Retrospective image co-registration using SPM5 software was performed on the prospectively corrected datasets as a measure of the residual motion remaining.

Results: Sample images acquired with the volunteer performing abrupt motions during the scan are shown in Fig. 1. Row 1 demonstrates the effectiveness of prospective correction to maintain the brain at a fixed position in the image reference frame throughout the time-series, while row 2 illustrates the result of similar motion as in row 1 but without correction. Fig. 2a plots the 6-DOF calculated from the active marker positions for the images in Fig. 1, row 1, illustrating the nature of the head motion. Fig. 2b shows the residual motion remaining after retrospective co-registration is performed on the prospectively compensated images; residual rotation (±0.2º) and translation (±0.2 mm) are comparable to resting levels, further evidence that the prospective strategy corrected for almost all of the motion. Fig. 3 shows similar plots for the smooth motion case (images not shown).

Fig. 1



The solid red line is referenced to the brain-center of the first dynamic (column 1) for each time-series (correction ON vs. OFF). The dashed lines highlight head motion relative to the first dynamic.

Fig. 2

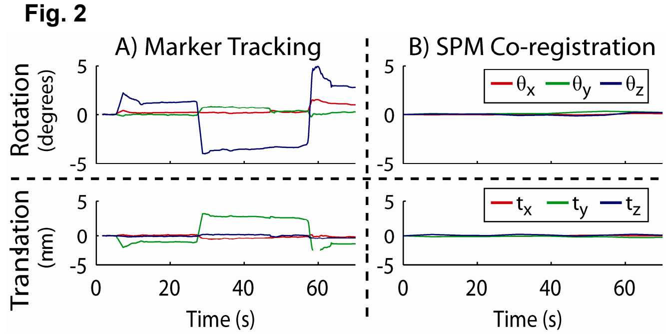
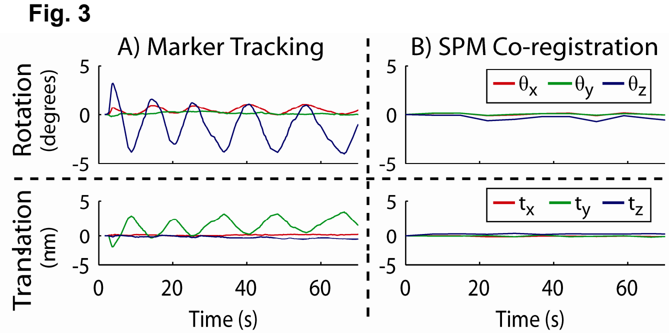


Fig. 3



Discussion & Conclusion: This work demonstrates utilization of active markers in a real-time motion correction package for EPI. High precision marker measurements (< 10 μm (11)) and image-plane corrections are completed in ~ 25 ms per slice, on-par with cloverleaf (4) and optical (6) strategies (18 ms and 32 ms, respectively), but without the need for cloverleaf's 12 s initial reference scan (during which the subject must remain motionless), or the additional hardware requirements of optical tracking. Also, techniques to use a receive channel for both imaging and active marker tracking via fast switches are available.

While image misalignment has been compensated for, a secondary effect of head motion is image distortion caused by changes in the effective shim within the brain as the head moves through the magnetic field; image distortion will potentially impact retrospective image-based motion estimates, and may account for the residual motion remaining in Fig. 2b, 3b. A real-time shim strategy combined with correction for bulk rigid-body motion may improve these results (12). Utility in other EPI-based applications, such as diffusion and perfusion imaging, will be avenues of future investigation.

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