fMRI with concurrent magnetic field monitoring

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INTRODUCTION: Functional brain MRI is notoriously strenuous on the gradient system, leading to heating and main field drifts, which can cause image shifts or, with spiral readouts, blurring. Long readout times in single-shot imaging make fMRI prone to image warping and/or artifacts. The former can partially be amended by image co-registration, which is problematic, however, at high resolution and for non-Cartesian trajectories. Extended scan sessions also entail physiologically induced field fluctuations (e.g. by deep breathing or shoulder movement) and subject motion, which may alter the magnetic field in the brain or require interventions by the operator. For these reasons, it is attractive to precisely know the spatio-temporal magnetic field evolution in the imaging volume during the scan. On the one hand, such knowledge can be taken into account for image reconstruction; on the other hand, it could be a useful means of subject surveillance and of monitoring the course of a study for retrospective analysis. Recent advances in field monitoring hardware and methods [1,2] actually promise to offer such capability. The present work aims to explore this proposition, using recent concurrent monitoring technology.

Fig.1: Concurrent magnetic field monitoring setup integrated in a 8-channel head coil; mirror for projection of the visual paradigm.

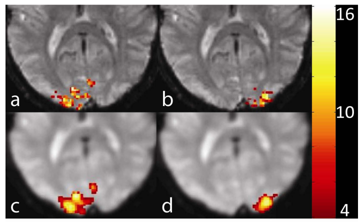

Fig.2: t-contrast maps (p=0.05 FWE-corrected) overlayed on an actual EPI dynamic showing highly significant differential activation in the hemifield-representation of the primary visual cortex, before (a/b) and after (c/d) smoothing.

METHODS: All measurements were performed with a 3rd-order (16-channel) concurrent field monitoring setup based on ^{19}F NMR [Fig. 1] [1], which was integrated in a commercial 8-channel head array and used in a Philips Achieva 3T system. ***Experiments:*** fMRI was performed with a visual paradigm consisting of block-wise stimulation of either the upper-left and lower-right (ULLR) visual hemi-fields or vice versa (LLUR); flickering colored wedges, 16s block length, 5s fixation, projected via a mirror. Readouts were performed by single-shot GRE EPI, SENSE reduction factor 2, matrix 126, T_{acq} 52ms, 30 slices, TR 3000ms, 456 dynamics (total 22.8min). One angulated transverse slice through the visual cortex was evaluated. An identical scan of 120 dynamics was run while the subject performed potentially confounding actions such as shrugging. Finally two gradient-free scans (TR 60ms) were performed to study physiologically induced field shifts in the head caused by regular and deep subject breathing. Throughout, field monitoring was performed concurrently without any sequence adjustments. ***Image Reconstruction:*** Dynamic phase coefficients up to 3rd order (k_0-k_{15}) were derived from the concurrent monitor data and used in an iterative higher-order reconstruction scheme [2], along with a B_0 map measured by two monitored spin-warp scans with ΔTE = 0.6ms). For comparison, images were also reconstructed i) without B_0 correction and ii) demodulating the imaging signals only by the mean of the B_0 map ('mean-B_0 correction'). No EPI phase correction or co-registration was performed in addition. ***SPM Analysis:*** A standard General linear model (GLM) analysis was performed based on raw images of the last 5min (neither realigned nor smoothed), using SPM8 (Functional Imaging Laboratory, London) to retrieve t-maps of differential activation for both conditions (ULLR-LLUR and LLUR- ULLR). This analysis was compared to a GLM of smoothed (Gaussian kernel, FWHM 4.5mm), but non-realigned images. The t-maps were corrected for multiple comparisons using family-wise error correction (FWE p=0.05). ***Subject Surveillance:*** Field fluctuations between consecutive dynamics were analyzed for the fMRI and the gradient-free scans. To this end, the difference of the 0th (k_0) and 1st (k_{1-3}) order phase coefficients relative to the 1st dynamic was computed and a linear regression was performed. This yielded 0th-order [Hz] and 1st-order field drifts, from which the maximum frequency change induced in a 20cm FOV was determined (Hz_{max}).

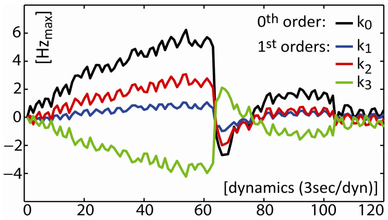

Fig.6: Frequency fluctuations (over the FOV) during the first 6min of the fMRI scan. The fast oscillations reflect breathing; a major motion event (head was shifted by 0.5mm) occurs after 190sec, a less pronounced one after 312sec.

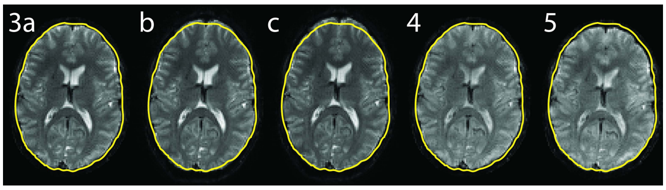

Fig.3: EPI image of dynamic 1 with a) full B_0 correction, b) mean-B_0 correction and c) without B_0 correction. **Fig.4:** EPI image of dynamic 361 which exhibits no shifting although the field has drifted by 41.4Hz as compared to dynamic 1. **Fig.5:** EPI image of dynamic 361 if the main field drift is not taken into account in the image reconstruction, resulting in a two pixel shift in phase encode direction. **Figs.3-5:** The yellow line depicts the contour of a conventional anatomic spin-warp image.

RESULTS: Subject positioning was not affected by the presence of monitoring setup ***SPM Analysis:*** Highly significant BOLD activation was found with all 4 analyses of the fMRI scan (Fig.2). Activation patterns are overlayed on the first EPI image of the underlying series. ***Image Reconstruction:*** Reconstruction based on the full field dynamics and including static B_0 correction yielded single-shot images free of evident artifacts and perfectly congruent with a spin-warp image (yellow contour, Fig. 3a). Non-B_0 corrected and mean-B_0 corrected images exhibit warping and/or shifting of up to 3 and 5 pixels respectively (Fig. 3b/c). After 18min, the main field had drifted by 41.4Hz, i.e. by slightly more than twice the pixel bandwidth of 19.2Hz. An image reconstructed based on the monitoring data is not affected by this drift (Fig.4a). However, when neglecting the 0th-order monitoring result, the image shifts by two pixels as expected (Fig. 4b). ***Subject Surveillance:*** Although the subject was instructed not to move, significant field fluctuations were observed during the fMRI scan (Fig.6). Besides small field fluctuations due to breathing (seen in 0th and 1st order), sudden motion apparently occurred after 3min (dynamic #63). According to inspection of the image series, the field drift around dynamic #63 was associated with subject motion by about 0.5 pixels. More drastic field changes were caused by deliberate subject motion in the shorter additional scan (0th/1st orders): 13Hz/7Hz_{max} by shrugging and 5Hz/10Hz_{max} by folding the arms across the chest. The gradient-free breathing scans revealed 0th-order fluctuations of about 4Hz/2Hz (deep/regular breathing) and similar effects in the 1st orders (1.2 Hz_{max}/3.5Hz_{max}).

DISCUSSION AND CONCLUSION: The results of this study indicate that concurrent field monitoring is an effective means of rendering fMRI more robust against common types of field drift and fluctuation. In combination with suitably modified image reconstruction, the monitoring approach permits accounting for these confounds without the need for any additional calibration or subject surveillance. It is thus particularly promising for fMRI at ultra-high-field, where physiological field fluctuations are even more pronounced, and for non-Cartesian readouts, which are often more susceptible to hardware imperfections. Enhanced image congruence over time and between different sequences is instrumental in fusing raw data with reference maps, e.g., for B_0 correction. Alternatively to or jointly with co-registration, it may also improve the fidelity of putting fMRI results in their anatomical context. Finally, it has been shown that knowledge of the dynamic field evolution contains potentially valuable information about a subject's breathing state and other types of motion, which may be useful for data analysis or as a basis of operator intervention or data rejection.

REFERENCES: [1] Barmet et al., Proc. ISMRM 2010, p216. [2] Wilm et al., Proc. ISMRM 2009, p562.