Single echo EPI sequence with dynamic distortion correction: minimization of errors due to motion and breathing.

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Introduction: The geometric distortions encountered in EPI can be corrected using field maps (FMs) calculated from a reference measurement, usually a dual echo Gradient Echo scan (GEFM)[1]. This "static" approach does not account for temporal B_0 changes over the course of an fMRI experiment. An alternative "dynamic" approach is to use a dual echo EPI for fMRI measurements and calculate FMs for each time point, a method known as DOCMA[2]. Dual echo EPI limits the achievable spatial and/or temporal resolution, however. A new, single-echo dynamic method called CURED was recently proposed to overcome this limitation[3]. In CURED, the echo time (T_E) is "jittered" between two values; one for the odd, another for the even time points, and FMs are calculated between adjacent volumes. These FMs are subject to errors, however, where there are substantial field changes between adjacent volumes, e.g. due to motion and breathing. In this study, the errors encountered in CURED are analysed and reduced via parameter optimization, and residual errors in both CURED and static FMs are quantified with respect to DOCMA (taken to be the gold standard). The effect of jittering the T_E on the BOLD sensitivity (BS) of CURED is investigated by comparison with standard EPI in two motor tasks.

Methods: The FM is proportional to the frequency offset, ω, which, in any voxel, can be expressed as $\omega_{t2}=\omega_{t1}+\delta\omega$, where t1 and t2 are successive time points and the change δω arises mainly due to breathing and motion. The phases at t1 and t2 can be approximated by $\Phi_{t1}=T_{E1}\cdot\omega_{t1}$ and $\Phi_{t2}=T_{E2}\cdot(\omega_{t1}+\delta\omega)$. These are used to generate CURED field maps: $FM_{CURED}=(\Phi_{t2}-\Phi_{t1})/\Delta T_E$. The error on FM_{CURED} is thus: $\delta\omega\cdot T_{E1}/\Delta T_E$ for odd, and $\delta\omega\cdot T_{E2}/\Delta T_E$ for even volumes. The errors can therefore be minimized by reducing T_R (which reduces δω), decreasing T_E or increasing ΔT_E. CURED was optimized and then assessed in three experiments, each of which was carried out on 3 volunteers with a 7 T Siemens scanner using a 32 channel head coil. Dual echo Gradient Echo scans were acquired for GEFM calculation, and respiration was recorded with a chest belt. **Exp.1**: quantification of breathing and motion related CURED errors as a function of ΔT_E (sequence optimization). Volunteers a) lay still and b) rotated their head slowly about the left-right axis during EPI runs. In order to be able to compare CURED to the gold standard (DOCMA), a dual echo version of CURED was used with 3.3x3.3x4.4mm^3 voxel size, T_R=1.2s and $T_{E,odd}$=[11, 31]ms and $T_{E,even}$=[11+ΔT_E, 31+ΔT_E]ms, where ΔT_E values of 0.8, 2, 4 and 6 ms were used. **Exp.2**: comparison of the accuracy of static and CURED unwarping in the presence of motion. Volunteers performed a head rotation after GEFM but before CURED EPI (1.6x1.6x4.4 mm^3 voxel size, T_R=1.2s, $T_{E,odd}/T_{E,even}$=19/25ms). **Exp.3**: comparison of BOLD sensitivity in CURED EPI (with the same parameters as in Exp.2) and standard single echo EPI (T_E=22ms) over 3 runs of block designed hand and foot tasks (A: rest, B: hand clench-release, C: foot flex in an ABACABACA design with 16 volumes per block).

Analysis: Voxel Shift Maps (VSM) were derived from all FMs [4]. In Exp.1, a voxel-wise difference between GEFM and CURED ($T_{E,odd}/T_{E,even}$=11/11+ΔT_E) VSMs and gold standard DOCMA VSMs was calculated and, for a selected ROI, plotted as a function of time (Fig.1, right). Root-mean-square (rms) error maps were calculated from VSM differences (Fig.1, center columns). In Exp. 3, the mean intensity difference between CURED odd and even volumes was subtracted from even volumes to remove magnitude fluctuations due to T_E jittering. Standard EPI and intensity corrected CURED data were slice timing and motion corrected and runs were coregistered prior to GLM analysis with SPM8. Hand and foot area mean t-values in the primary motor cortex were calculated for each subject.

Results: **Exp.1**: with a short ΔT_E (0.8ms), breathing-related errors were higher in CURED than GEFM (≈1 voxel peak-to-peak in ROI; Fig.1, 1st row). CURED errors reduced with increasing ΔT_E, reaching a similar level as in GEFM for ΔT_E =6ms (Fig.1, 2nd row). A ΔT_E value of 6ms (which leads to residual breathing-related errors of ≈0.15 voxel peak-to-peak), was used for all subsequent CURED measurements. In the head drift experiment, errors were much higher for GEFM, especially at the edge of the brain (Fig.1, 3rd row, blue arrows). The error plot shows how GEFM diverges from DOCMA with head movement while CURED remains accurate. Residual small errors in CURED (≈0.4 voxel) arise from breathing (frequency ≈ 0.36 Hz) and motion effects. **Exp.2**: for data with motion between GEFM and EPI (sum rotation≈12°) static unwarping worsened distortions (up to 8mm) in the occipital lobe, rather than correcting them (Fig.3c). No residual distortions were apparent with CURED (Fig.3d). **Exp.3**: Hand activation maps derived from standard and CURED data are in a good agreement (Fig.3), and there was no difference in mean t-values in either task (hand: p=0.593, foot: p=0.109; Wilcoxon Sign Rank Paired Tests with $p<0.05$).

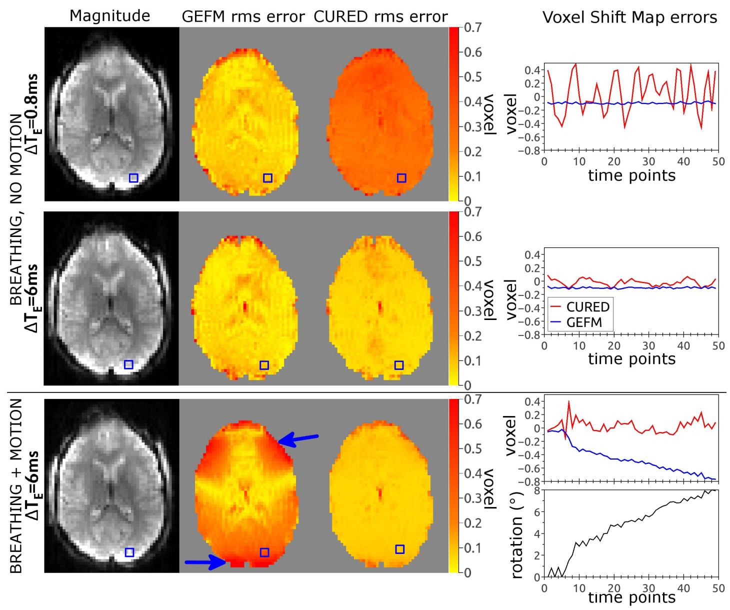

Fig.1: Quantification of GEFM and CURED errors in breathing or breathing+motion condition. Colored maps: root-mean-square error maps. Plots: CURED and GEFM VSM errors in selected ROIs (blue squares) as a function of time. In motion case SPM8 rotation estimates are plotted in black.

Discussion and Conclusion: CURED is a single-echo dynamic field mapping method that, with parameter optimization, yields accurate maps of local deviations from B_0 even in the presence of motion without compromising BOLD sensitivity or spatiotemporal resolution and without the need for a reference scan. Small breathing-related errors in CURED (<0.15 voxel) with ΔT_E=6ms and T_R=1.2s can be further reduced by reducing T_R (e.g. by using simultaneous multi-slice EPI[5]). Breathing-related errors studied can be expected to affect other distortion correction methods, such as PLACE[6].

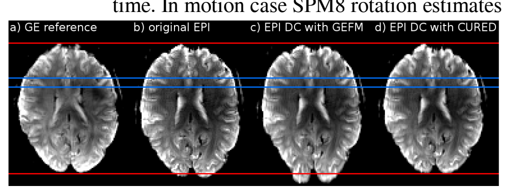

Fig.2: The accuracy of c) static and d) dynamic dist. corr. (DC) in comparison with a) distortion-free reference.

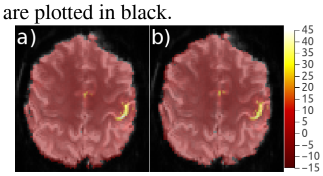

Fig.3: a) standard EPI and b) CURED hand activation maps overlaid on the mean EPI.

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Ref: [1] Jezzard P and Balaban RS (1995) *MRM* 34:p65. [2] Visser E, et al. (2012) *MRM* 68:p1247. [3] Dymerska B, et al. Proc. ISMRM 2014, #4915. [4] Robinson S and Jovicich J (2011) *MRM* 66:p976. [5] Setsompop K, et al. (2012) MRM 67:p1210. [6] Xiang QS and Frank QY (2007) *MRM* 57:p731.