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Extended hybrid-space SENSE for EPI: Off-resonance and eddy current corrected joint interleaved blip-up/down reconstruction

Benjamin Zahneisen*, Murat Aksoy, Julian Maclaren, Christian Wuerslin, Roland Bammer

Stanford University, Department of Radiology, Stanford, CA, United States

A B S T R A C T

Introduction: Geometric distortions along the phase encode direction caused by off-resonant spins are still a major issue in EPI based functional and diffusion imaging. If the off-resonance map is known it is possible to correct for distortions. Most correction methods operate as a post-processing step on the reconstructed magnitude images.

Theory and methods: Here, we present an algebraic reconstruction method (hybrid-space SENSE) that incorporates a physics based model of off-resonances, phase inconsistencies between k-space segments, and T2*-decay during the acquisition. The method can be used to perform a joint reconstruction of interleaved acquisitions with normal (blip-up) and inverted (blip-down) phase encode direction which results in reduced g-factor penalty.

Results: A joint blip-up/down simultaneous multi slice (SMS) reconstruction for SMS-factor 4 in combination with twofold in-plane acceleration leads to a factor of two decrease in maximum g-factor penalty while providing off-resonance and eddy-current corrected images.

Conclusion: We provide an algebraic framework for reconstructing diffusion weighted EPI data that in addition to the general applicability of hybrid-space SENSE to 2D-EPI, SMS-EPI and 3D-EPI with arbitrary k-space coverage along z, allows for a modeling of arbitrary spatio-temporal effects during the acquisition period like off-resonances, phase inconsistencies and T2*-decay. The most immediate benefit is a reduction in g-factor penalty if an interleaved blip-up/down acquisition strategy is chosen which facilitates eddy current estimation and ensures no loss in k-space encoding in regions with strong off-resonance gradients.

Introduction

Geometric distortions in echo planar imaging (EPI) (Mansfield, 1977) are a fundamental problem and generally require some sort of correction (Jezzard, 2012). Local off-resonances, due to shim imperfections in combination with the low readout bandwidth along the phase encode direction in an EPI train, lead to a spatial shift of the reconstructed voxel along the phase encode direction. Geometric distortions can lead to errors when registering the functional imaging data to an undistorted anatomical scan and voxels might be shifted on top of each other and become indistinguishable.

The same mechanism is responsible for eddy-current distortions in diffusion weighted imaging (DWI) and diffusion tensor imaging (DTI). Here, the off-resonances are not caused by shim imperfections due to susceptibility changes within the brain but by residual eddy currents in the gradient coils due to the strong gradient pulses used for diffusion weighting. Especially in DTI this is a major problem because the eddy-current distortions depend on the diffusion direction which causes a misalignment of voxels from different volumes that are used to fit a tensor model to the data and thereby resulting in a blurring effect.

Methods to correct for geometric distortions in EPI were presented by (Jezzard and Balaban, 1995) and (Weisskoff and Davis, 1992). Both approaches acquire a field map as a separate scan (Schneider and Glover, 1991) in order to calculate a 1D pixel shift map. The pixel shifts are subsequently corrected in the image domain by 1D interpolation along the phase-encode direction. A similar method uses the EPI acquisition itself to estimate the fieldmap (Reber et al., 1998) by acquiring a set of images within a range of echo time (TE) values. As in the previous approach, 1D resampling in the image domain unwinds voxel shifts. Both methods can be classified as field-mapping approaches as they use the underlying off-resonance field to infer the pixel shift map, taking into account specific EPI acquisition parameters like echo spacing and effective readout duration.

A second class of correction methods aim at measuring the pixel shift map directly, commonly referred to as point-spread-function (PSF) mapping. The measured image is the convolution of the

* Correspondence to: Stanford University, Department of Radiology, 1201 Welch Rd, Stanford, 94025 CA, USA.
E-mail address: benjamin.zahneisen@gmail.com (B. Zahneisen).

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undistorted voxel intensity and the PSF (Robson et al., 1997) and (Zaitsev et al., 2004). Off-resonance correction is performed by deconvolving the acquired image with the measured PSF. An overview and a comparison between field mapping and point spread function mapping techniques can be found in (Zeng and Constable, 2002). They conclude that the PSF approach provides a superior solution to the problem of geometric and intensity distortions in EPI compared to field map approaches.

For non-Cartesian trajectories like spirals the effect of off-resonances on the PSF is not a simple spatial shift but a more complex blurring. In (Sutton et al., 2003) the field effects are modeled in the forward signal equation used to reconstruct the spiral data by means of a conjugate gradient SENSE approach (Pruessmann et al., 2001). If field effects are included, the forward model is no longer a Fourier Transform and the highly computationally efficient non-uniform FFT (NUFFT (Fessler, 2007)) can no longer be used. (Sutton et al., 2003) provided an approximation to the full solution known as time segmentation.

Dynamic variations in off-resonance pose another challenge for most EPI applications. On top of a static off-resonance map dynamic fluctuations like eddy-current effects in DWI or respiration induced shim changes in fMRI, cause additional changes. A common strategy to measure dynamic fieldmaps is based on relative changes of the phase of the EPI time series. Dynamic fieldmaps are derived, either by slightly shifting the echo time (Dymerska et al., 2016; Visser et al., 2012) or from a change in image phase directly (Ooi et al., 2013).

The widely used blip-up/down approach is another fast and robust way to estimate the distortion field, i.e. the distorted PSF, from only two EPI acquisitions with inverted phase encoding direction (Andersson et al., 2003, 2001) and (Holland et al., 2011) and implemented in FSL (Smith et al., 2004) as *topup*. Local distortions occur in opposite directions, compressed in the blip-up scan and stretched in the blip-down scan, or vice versa. For otherwise identical readout parameters the true voxel position is halfway in-between the blip-up and -down case.

Limitations of off-resonance correction

Knowing the fieldmap allows one to directly or indirectly account for the additional phase evolution during the reconstruction process and thereby canceling its effect on the PSF. In the case of spin-echo EPI we can neglect complete voxel dephasing due to local gradients at tissue/tissue or tissue/air boundaries with large susceptibility differences. However, these local gradients can balance or even invert the gradients imposed by the nominal k-space trajectory of the phase encoding direction. The phase evolution of each voxel is then no longer unique or the local trajectory never reaches the center of k-space. This leads to an ill-posed reconstruction problem requiring prior information to be numerically stable. This effect is extensively discussed in (Andersson et al., 2001) and can be easily visualized in image space by the finding that only stretched voxels can be corrected whereas signal pile up in a single voxel is impossible to disentangle. We know that by inverting the phase encoding direction we also invert the direction of geometric distortions; e.g. stretched voxels get compressed and vice versa. The blip-up/down strategy (Andersson et al., 2003) exploits this phenomenon by acquiring two sets of data, one with regular phase encoding direction and one with inverted phase encoding direction. During the correction process, based on the fieldmap, one can identify regions with signal pile up in one acquisition mode and pick the information from the corresponding stretched region from the other mode.

Parallel imaging, simultaneous multi-slice and EPI reconstruction

The scale of geometric distortions ultimately depends on the time between two k-space lines, i.e. the echo spacing, of the fully sampled k-space. Parallel imaging (SENSE (Pruessmann et al., 1999), GRAPPA (Griswold et al., 2002)) offers the possibility to shorten the effective echo spacing while not relying on segmented (interleaved) EPI. However, parallel imaging acceleration reduces distortions but does not automatically translate to shorter volume TRs because a significant amount of time is spent on signal excitation and fat suppression and, in the case of DW-EPI, on diffusion preparation. By employing simultaneous multi slice (SMS) imaging, the volume TR can be reduced by the SMS-factor. The g-factor penalty associated with the slice separation based on coil sensitivity variation can be greatly reduced by employing the blipped-CAIPI method (Setsompop et al., 2012) which effectively leads to a better distribution of aliased voxels from different slices similar to the original CAIPIRINHA technique (Breuer et al., 2005). The slice-GRAPPA method and its derivatives perform the SMS reconstruction by treating it as a concatenation of 2D slices with slice offset dependent CAIPI shifts and slice-dependent GRAPPA kernels.

An alternative reconstruction approach is based on the formulation of SMS-encoding in terms of a 3D k-space (Zahneisen et al., 2014b; Zhu et al., 2012) where the in-plane and the SMS acceleration are essentially treated identically in k-space by using a 2D-GRAPPA method (Zhu et al., 2013) or in the image domain by using a 2D-SENSE approach (Hennel et al., 2015; Zahneisen et al., 2014a).

The recently proposed hybrid-space SENSE method (Zhu et al., 2016) is an algebraic reconstruction that, after stripping the fully sampled x-direction, directly inverts the encoding matrix in the hybrid x-k_y-k_z-space and can therefore handle arbitrary, non-periodic CAIPI blip patterns. It was also shown that slice dependent ghost correction terms could be included in the reconstruction process (Zhu et al., 2016).

Off-resonance corrected and joint blip-up/down EPI reconstruction

In this work we present an extension of the hybrid-space SENSE method that models off-resonance effects, T2* decay and motion-induced phase errors. By explicitly modeling these effects we automatically correct for them during the reconstruction. One immediate advantage is that we reconstruct complex data, which retains Gaussian noise properties compared to less favorable Rayleigh noise in the case of magnitude operations in the image domain. By performing a joint reconstruction of a segmented k-space acquisition where one segment is acquired in blip-up mode and the 2nd segment in blip-down mode, we can simultaneously estimate the distortion field due to off-resonances and eddy currents and reduce the g-factor penalty in the case of accelerated acquisitions. The joint reconstruction ensures that we make optimal use of available k-space information especially in regions with strong off-resonance gradients. We make use of established methods to estimate the distortion field in the image domain, namely FSL's *topup*.

Theory

Off-resonance corrected algebraic reconstruction including regularization

In theory, off-resonances affect all acquired k-space samples. However, for an EPI type acquisition one can safely ignore off-resonance effects along the readout direction because of the short acquisition along the read direction compared to the slow phase encoding direction. By performing a 1-dimensional Fourier Transformation along the k_x-domain the k-space data $s(k_x, k_y, k_z)$- is transformed to (x,k_y, k_z)-hybrid space (Zhu et al., 2016).

The signal from receiver coil i, $s_i(x=x_n,t)$ at spatial position x_n and as a function of time t from the start of EPI readout, can be written as

$$s_i(x=x_n,t) = \sum_{y=1}^{Ny} \sum_{z=1}^{Nz} m(x_n,y,z) C_i(x_n,y,z) e^{i\Phi(x_n,y,z,t)} R(x_n,y,z,t) \qquad (1)$$