Distortion correction of multi-coil diffusion-weighted EPI using the phase-based method: PLACE

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Introduction

EPI sequences are inherently sensitive to B_0 inhomogeneity causing distortions along the phase encode (PE) direction, particularly for single-shot images [1]. A simple method has been proposed to correct for EPI distortions by exploiting two EPI acquisitions that differ by a single "blip" in the PE direction. This method, called PLACE (Phase labeling for additional coordinate encoding) [2], uses an extra phase "blip" to encode the PE coordinate. Recently, PLACE has been successfully applied to diffusion weighted images (DWIs) of human brain from a single-channel receiver coil [3]. To extend this method to multi-channel receiver coil acquisitions, the data from each coil must be combined while preserving the phase information required by PLACE. However, multi-coil data is usually combined using the square root of the sum-of-squares (rSOS) to avoid unwanted signal cancelation resulting from inter-channel phase inconsistencies. The rSOS results in magnitude images, precluding the use of PLACE. A new method has recently been presented to perform a PLACE-like EPI distortion correction in combination with a parallel imaging for phased-array coils [4]. However, this method is complicated to implement as it uses modified k-space trajectories and SENSE reconstruction. Here we propose a simple method to combine the complex signal from many coils when two EPI acquisitions, with a particular phase relation, are acquired (such as those for PLACE). The method is conceptually the same as that used for multi-coil phase contrast angiography [5]. Using this method to combine multi-coil data, we show that the distortion of phased array EPI DWIs can be corrected using PLACE.

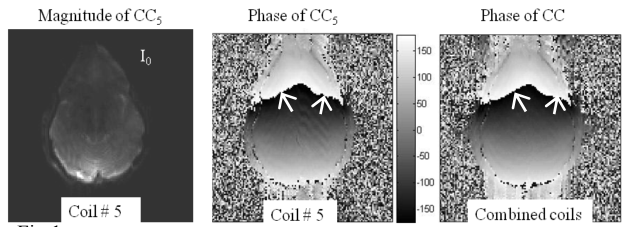

Fig.1

Theory

PLACE uses the phase relation between the two EPI images, acquired with and without extra "blip", to encode location by creating an expected phase ramp. B_0 inhomogeneity causes a distortion of the phase relation and restoration of the expected phase ramp can be used to correct the distortion. It was shown [3] that to correct DWIs, the non-diffusion weighted image (b=0), I_0, can be used to produce a distortion correction map whilst the DWIs cannot due to unpredictable phase distortions caused by the diffusion sensitizing gradients. However, the I_0 correction map can be used to successfully restore the signal from the DWIs to its correct location along the PE direction.

Although the inter-coil phase relation of each individual EPI PLACE image is unknown, the phase relation between the two EPI PLACE images is known: it is a distorted phase ramp. For N coils, writing the complex EPI signal with and without extra "blip" at a given coil #n, as $C1_n$ and $C0_n$ respectively, one can define a phase difference coil image as: $CC_n = C0_n \cdot C1_n^* / \|C1_n\|$ where * indicates complex conjugate and $\|C1_n\|$ is the magnitude of $C1_n$. It is clear that the phase of CC_n will equal the distorted phase ramp for coil #n which should be the same for all n (n=1-N). Combining CC_n by complex averaging: $CC = (\Sigma_{n=1\text{-}N}\, CC_n)/N$, inherently weights the phase ramp contribution from each individual coil by the pixelwise magnitude, resulting in a combined complex image, CC, with phase, arg{CC}, equal to the sought correction phase map.

Method

Data were acquired on a 3T scanner (MR750, GE Healthcare) with an 8-channel phased-array headcoil. A slightly modified standard DWI sequence was used: with and without an extra "blip" equivalent to skipping 2 k-space lines in the PE direction. A DWI data set, consisting of I_0 as well as DWIs acquired with diffusion sensitizing gradients (b=1000) along each of the three orthogonal directions: DWI_x, DWI_y, DWI_z , was obtained for the brain of a healthy volunteer. The I_0 data from each coil was processed separately as explained above to yield CC_n for n=1-8. The results were complex averaged to yield CC and this was used to obtain the phase ramp required for PLACE. This correction map was used to remove the distortion seen in the rSOS magnitude images of the DWI data set which were then used to produce a corrected apparent diffusion coefficient (ADC) map: $\langle DWI \rangle = I_0 \exp(-b \cdot ADC)$ where $\langle DWI \rangle = (DWI_x + DWI_y + DWI_z)/3$.

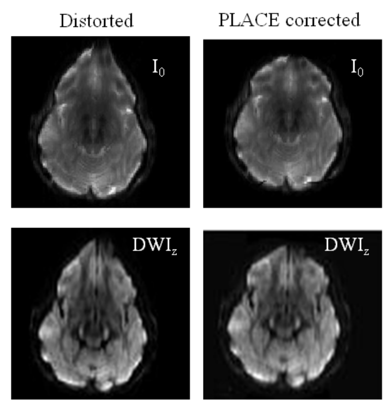

Fig.2

Results

For I_0, the phase difference coil images, CCn, were similar and contained the distorted phase ramp. Regions of low signal resulted in noisier phase (see arrows in Fig.1) but the complex average weighted these appropriately, resulting in a smooth distorted phase ramp contained in arg{CC}. This phase map was successfully used to correct the distortion of the magnitude (rSOS) DWIs (Fig.2). Figure 3 shows the resulting ADC map in comparison to a spin-echo (SE) reference image. The improvement is particularly noticeable in frontal regions on this slice (arrows) but is apparent throughout.

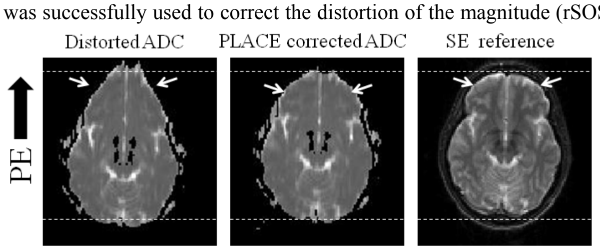

Fig.3

Conclusion

Phase difference image maps for each coil can be combined to yield a smooth distortion correction phase map required for PLACE. Use of this combined phase map can then successfully correct all the magnitude images in the DWI data set. Application of PLACE for EPI DWI distortion correction of phased array data in other anatomical regions (eg. prostate) is currently underway.

References [1] Jezzard et al., MRM 34, 1995 [2] Xiang et al., MRM 57, 2007 [3] Chavez et al., ISMRM #5064, 2010
[4] Techavipoo et al., MRM 61, 2009 [5] Bernstein et al., MRM 32, 1994