Accelerated Point Spread Function Mapping Using Signal Modelling for Accurate EPI Geometric Distortion Correction

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Introduction: Single-shot echo-planar imaging (EPI) is a fast technique allowing the acquisition of an image following a single RF excitation. The high temporal resolution of EPI makes it the method of choice for applications such as fMRI or diffusion tensor imaging. However, EPI is prone to geometric and intensity distortions in the presence of magnetic field inhomogeneities. Several correction techniques have been proposed based on field map acquisitions [1] or point spread function (PSF) acquisitions [2]. The correction based on the PSF technique is very robust avoiding complicated 2D phase unwrapping often required by the dual-echo field mapping techniques. Meanwhile, the acquisition of the PSF data is relatively long. Parallel imaging techniques such as GRAPPA have been employed for accelerating the PSF data acquisition [3]. In this work, we propose a new method based on the modelling of the PSF data signal to allow accelerated acquisition for accurate geometric distortion corrections.

Theory: The PSF mapping sequence is based on the traditional blipped EPI readout with the phase encoding (PE) prewinder being replaced by a gradient table. Figure 1(a) represents the k_{PE} – k_{PSF} space coverage performed during the acquisition of the PSF data. The white and black dots represent data points from the odd and even echoes acquired in opposite directions. In Fig. 1(a) the data represented at the left are acquired with the strongest phase encoding prewinder and the data represented at the right are acquired with no phase encoding prewinder. Figure 1(b) shows the 3D space in the x, y, k_{PSF} coordinates that is obtained after performing a Fourier transform in the read direction and in the phase encoding direction. In this x, y, k_{PSF} 3D-space, when a strong prewinder is applied, the echo occurs at a later time compared to the k_{PSF} encoding steps which have a very weak prewinder. Considering the T_2* signal decay typical in gradient-echo EPI, for a given point of (x_0, y_0) coordinates (see Fig1.b) the magnitude of the signal along the k_{PSF} dimension will depict an exponential shape with small oscillations. These oscillations are due to a multiplication in the kx-ky space with a sliding rectangular function. In absence of geometric distortions, according to the Fourier shift theorem, each image will have a ramp of phase over the entire FOV in the PE direction from $-\pi \cdot n_{PSF}$ to $\pi \cdot n_{PSF}$ with n_{PSF} ranging from $-N_{PSF}/2$ to $N_{PSF}/2-1$, where N_{PSF} is the number of PSF encoding steps. In presence of geometric distortions, deviations from these ramps will be observed. These deviations allow the quantification of the local distortions in the EPI data. This concept is a generalisation of the PLACE method [4] which estimates distortions using only two images in the centre of the k_{PSF} space corresponding to n_{PSF} = 0 and 1.

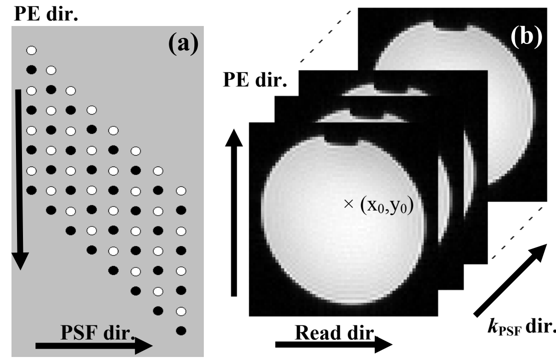

Fig. 1. **(a)** k_{PE} – k_{PSF} space coverage performed during the acquisition of the PSF data. **(b)** Illustration of the x, y, k_{PSF} 3D-space data obtained after Fourier transform in read and phase encoding direction. The local pixel displacement is estimated using this 3D space.

Material and Methods: Fully sampled PSF data sets of phantom and healthy volunteers were acquired on a Magnetom Tim Trio 3T clinical scanner (Siemens Healthcare, Erlangen, Germany). Undersampling factors up to 12.8 in the PSF-encoding direction were subsequently simulated by using a maximum of ten k_{PSF} encoding steps. Data processing was automatically performed off-line with custom-made software developed in Matlab. After performing a Fourier transformation in the readout direction (operation including linear phase correction) and in the PE direction, the distortions can be estimated in the x, y, k_{PSF} space. After removing the corresponding PSF encoding phase ramp from each image, a linear fit is performed on the remaining unwrapped phase values in order to calculate the local distortion. As demonstrated by Conturo and Smith [5], the precision of the phase measurement is proportional to the SNR of the magnitude image. For this reason, a weighted linear fit was applied instead of a linear fit. These considerations allow establishing an optimal acquisition pattern in the undersampled k_{PSF} direction, sampling data with high magnitude (corresponding to a weak prewinder) more densely. The optimal sampling pattern contains three to four sufficiently close points ($\Delta k_{PSF\ undersampled} \leq 4 \cdot \Delta k_{PSF\ full\ sampled}$) with a weak phase prewinder and gradually increasing distance between samples towards the direction of increasing phase prewinder. For severe geometric distortions, if the subsequent k_{PSF} steps are too distant, an undetected phase wrap might occur. In this case, an initial guess of the resulting fit is calculated using the three sufficiently close k_{PSF} steps. The remaining values are unwrapped by adding/subtracting multiples of 2π such as they become as close as possible to the previously calculated line. Afterwards, a second weighted linear fit is performed, the resulting slope being proportional to the local distortion. The pixel shift maps were derived using the weighted linear fit in every point of the image. Regions exhibiting only noise were excluded via a threshold operation. The original PSF method offers the flexibility to calculate the pixel shift map in coordinates of either the distorted image or the undistorted GE image. In this work, the pixel shift map can only be calculated in the coordinates of the distorted image.

Results/Discussion: Figure 2 displays the results obtained for the *in vivo* experiment with a simulated acceleration factor of 12.8 in the PSF encoding direction (10 out of 128 k_{PSF} steps are used). Figure 2*a* illustrates an example of one distorted EPI images extracted from the whole brain slice package. The corresponding pixel shift map in the distorted coordinates is displayed in Figure 2*b*. The pixel shift map obtained with the undersampled data was compared to the pixel shift map obtained using the fully sampled data. For each experiment that was performed the maximum error was below 0.15 pixels (the selected threshold). This maximum error scales with the acceleration factor. For higher acceleration factors the maximum error between the fully sampled data and the undersampled PSF data increases to values superior to 0.15 pixels. In Figure 2*c* the corresponding corrected EPI image is displayed. To estimate the accuracy of the method the distortion-free gradient echo images were used as a reference. An edge detection algorithm applied to the non-distorted GE image was used to highlight the borders of the brain and the brain structure. This information was overlaid with the corrected EPI images to estimate the accuracy of pixels remapping operation (Fig. 2*d*).

Conclusions: This work demonstrates that the presented technique can be used for an accurate estimation of geometric distortions in EPI images, using a very limited number of k_{PSF} steps.The proposed method was robust, completely automated and did not require intensive computations.

Conflict of Interest: This project is developed in collaboration with Siemens Healthcare, Erlangen, Germany. Grant support from Siemens Healthcare.

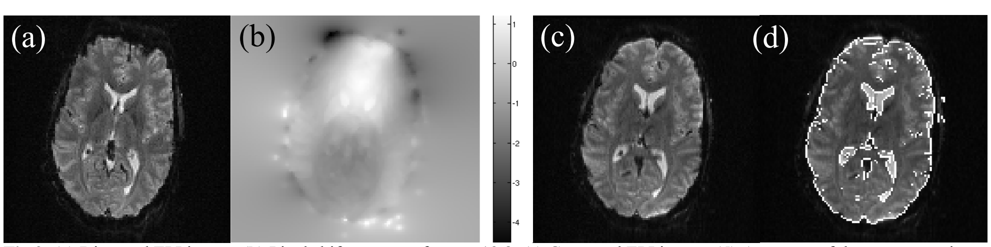

Fig 2: **(a)** Distorted EPI image; **(b)** Pixel shift map acc. factor =12.8; **(c)** Corrected EPI image; **(d)** Accuracy of the reconstruction.

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