Model based joint B0 and image estimation framework for dynamic field mapping and signal pile-up correction in prostate diffusion MRI

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Synopsis

Prostate diffusion MRI is recognized as a potential biomarker for tumour detection but currently it is unusable in some patients due to significant distortions. We proposed a novel model based joint image and B_0 reconstruction framework that can correct these distortions by using data acquired from opposite phase encoding gradient directions. Using sampling time shift between the two acquisitions, the proposed method is robust against any dynamic changes in the off resonance effects in the prostate-rectal air region.

Introduction

Prostate diffusion MRI scans are used as a potential biomarker for tumour detection. However, currently these are unusable in some patients due to distortions including signal pile-up and signal drop-out in the images. These distortions occur due to difference in susceptibility values at prostate and rectal-air interface.Techniques have been proposed that can correct for geometric distortions using a B_0 map acquired in separate scan that measures the off resonance frequency offset at different spatial locations. However,distortion correction using a previously acquired B_0 map may fail in case of 1)change in size of rectal air region across time,2) physiological motion,3)scanner frequency drift and 4) B_0 map errors in low SNR regions.In this work,using a set of single shot EPI data acquired in blip-up and blip-down phase encoding directions with a k-space sampling time shift between the two acquisitions,model based joint image and B_0 estimation framework is proposed that can account for any dynamic changes in the off resonance effects between B_0 and EPI scans; and can compensate for geometric distortions in the reconstructed EPI images.Results are presented for simulated data generated with realistic prostate B_0 maps and timings corresponding to a diffusion EPI acquisition.

Method

The proposed framework (Fig.1) acquires two EPI data sets (blip-up and blip-down) in opposite phase encoding gradient directions with a constant time shift (T_{diff}) between acquisition of k-samples in the two scans.Starting from an initial B_0 field estimated from reconstructed images in the two scans,a joint estimation framework is proposed that can estimate both corrected EPI image and corrected field maps.Let $\mathbf{Y_1}$ and $\mathbf{Y_2}$ be the k-space for blip-up and blip-down EPI scans, respectively. Mathematically, we can write[1,2]:

$$\mathbf{Y_1}(k,l) = \sum_{n=0}^{N-1}\sum_{m=0}^{M-1} \mathbf{x}(m,n) e^{-i2\pi(mk/M+nl/N)} e^{-i2\pi(\mathbf{\Delta B_0}(m,n).t_1(k,l))}$$
$$\mathbf{Y_2}(k,l) = \sum_{n=0}^{N-1}\sum_{m=0}^{M-1} \mathbf{x}(m,n) e^{-i2\pi(mk/M+nl/N)} e^{-i2\pi(\mathbf{\Delta B_0}(m,n).t_2(k,l))}$$

Eq(1)

where m,n are image coordinate indices, M,N are image dimensions, k,l are k-space coordinate indices, $\mathbf{\Delta B_0}$ is the B_0 field in Hz; $t_1(k,l)$ and $t_2(k,l)$ are the acquisition times of location (k,l) in k-space for blip-up and blip-down scans, respectively such that $t_2(k,l) = -t_1(k,l) + T_{diff}$, where T_{diff} is a constant time shift, the value is set in range of 1-3 msec. For spin echo sequence, time shift T_{diff} can be achieved by shifting the timing of the refocussing pulse in the sequence development. Eq (1) can be summarized as $\mathbf{Y_1}=\mathbf{E_1}(\mathbf{\Delta B_0})\mathbf{x}$ and $\mathbf{Y_2}=\mathbf{E_2}(\mathbf{\Delta B_0})\mathbf{x}$, where $\mathbf{E_1}$ and $\mathbf{E_2}$ summarize the encoding operators for blip-up and blip-down scans, respectively. The data from both phase encoding directions can be combined into a single formulation in Eq(2) by setting $\mathbf{Y}=[\mathbf{Y_1}\ \mathbf{Y_2}]^T$ and $\mathbf{E}=[\mathbf{E_1}\ \mathbf{E_2}]^T$ in Eq (1).

$$\mathbf{Y} = \mathbf{E}(\mathbf{\Delta B_0})\mathbf{x} \qquad Eq(2)$$

The proposed joint image and B_0 field estimation framework can be summarized as:

$$argmin_{\mathbf{x},\mathbf{\Delta B_0}} \mathbf{\Psi}(\mathbf{x}, \mathbf{\Delta B_0}) \qquad Eq(3)$$

where

$$\mathbf{\Psi}(\mathbf{x}, \mathbf{\Delta B_0}) = \|\ \mathbf{Y} - \mathbf{E}(\mathbf{\Delta B_0})\mathbf{x}\ \|^2 + \boldsymbol{\beta}_1 R(\mathbf{x}) + \boldsymbol{\beta}_2 R(\mathbf{\Delta B_0})$$

where $R(\mathbf{x})$and $R(\mathbf{\Delta B_0})$ are quadratic regularization terms $||\mathbf{Dx}||^2$ and $||\mathbf{D\Delta B_0}||^2$ respectively, $\mathbf{D}$ being the first order finite difference operator; β_1,β_2 are regularization weights.

The above formulation is solved using alternating minimization scheme[3,4].The image update in the k^{th} iteration is estimated using a previous field map estimate $\mathbf{\Delta B_0}^{k-1}$:

$$\mathbf{x}^k = argmin_{\mathbf{x}} \parallel \mathbf{Y} - \mathbf{E}(\mathbf{\Delta B_0}^{\mathbf{k-1}})\mathbf{x} \parallel^2 + \boldsymbol{\beta}_1 R(\mathbf{x}) \quad Eq(4)$$

Using estimate $\mathbf{x}^k$,the updated field map in the k^{th} iteration is estimated as:

$$\mathbf{\Delta B_0}^k = argmin_{\mathbf{\Delta B_0}} \parallel \mathbf{Y} - \mathbf{E}(\mathbf{\Delta B_0})\mathbf{x}^{\mathbf{k}} \parallel^2 + \boldsymbol{\beta}_2 R(\mathbf{\Delta B_0}) \quad Eq(5)$$

The above two step iterative process is repeated until the convergence is achieved.

Experiments

Scanning was performed on a 3T scanner (Achieva,Philips Healthcare). For B_0 field,a 3D dual echo gradient echo scan was performed with parameters:resolution= 2mm isotropic,FOV=200x200x70mm^3,TE1/TE2/TR=4.6/6.9/8.7msec,scan time=1 min.For reference,T2W images were acquired with parameters:resolution=2x2x4mm^3,FOV= 180x180x55mm^3,SENSE acceleration factor=2,TE/TR=100/4700 msec,scan time= 40 sec. EPI single shot distortion corrupted data with SENSE factor=2 was simulated from reference T2W data using B_0 field and simulated timings corresponding to a diffusion EPI acquisition (echo spacing=0.7 msec,echo train duration=38.2 msec).The initial B_0 was estimated from the reconstructed images $\mathbf{x_1}$ and $\mathbf{x_2}$ using regularized least squares field map estimation method[5].The proposed joint image and B_0 map reconstruction was compared against uncorrected reconstruction and correction using initial B_0 map.The effect of different time shifts (T_{diff}=1,2.3,5 and 10msec) on joint reconstruction is also investigated.

Results and Discussion

For T_{diff}=2.3 msec, reconstructions from different methods are shown in Fig. 2. The initial estimated B_0 map was not able to correct for all distortions. Most of the distortions including the pile up artefacts were corrected with proposed method. Fig. 3 shows the effect of different time shifts on the joint reconstructions. Reasonable reconstructions were achieved for T_{diff} =1 and 2.3msec. At higher T_{diff}>=5msec,additional artefacts were introduced in regions of high B_0 inhomogeneity due to phase wrapping. In future, the proposed framework will be investigated for invivo diffusion weighted data.

Acknowledgements

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References

[1] Munger et al, TMI 2000

[2] Usman et al, MRM 2018

[3] Matakos et al, ISBI 2010

[4] Fessler et al, "Michigan Image Reconstruction Toolbox," available at https://web.eecs.umich.edu/~fessler/code/index.html

[5] Funai et al, TMI 2008

Figures

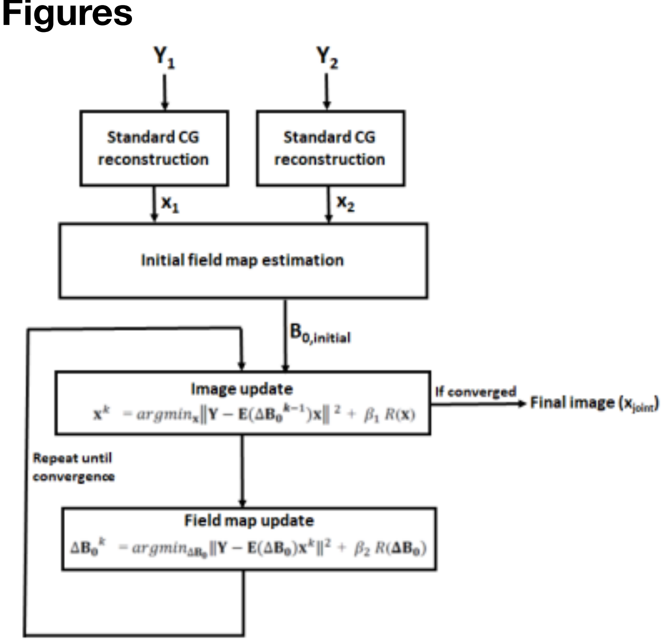

Fig 1: Implementation of Model based joint B_0 and image estimation framework using data $\mathbf{Y_1}$ and $\mathbf{Y_2}$ from blip up and blip down EPI scans with sampling time shift T_{diff}=1-3msec between the two acquisitions. Starting with a B_0 map ($B_{0,initial}$) estimated from standard Conjugate Gradient (CG) reconstructed images $\mathbf{x_1}$ and $\mathbf{x_2}$ from the two scans, in each iteration of the algorithm, we update both B_0 and reconstructed image using alternating minimization scheme (Eq 4 and Eq 5). The convergence is achieved when the residual in the current iteration becomes smaller than ɛ (ɛ being a small number) giving the final distortion corrected output image

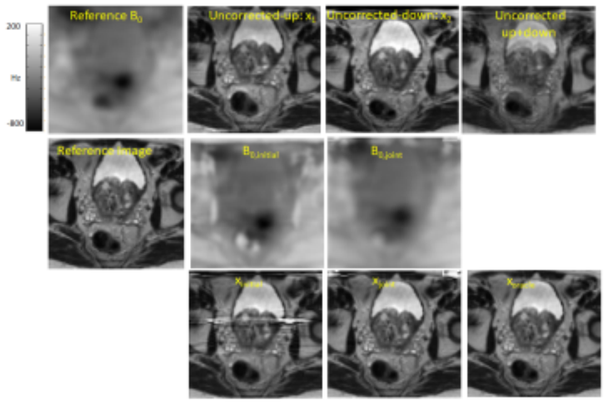

Fig.2: Reconstruction Results for simulated single shot EPI data with time shift T_{diff}=2.3 msec between blip-up and blip-down scans. The uncorrected reconstructions $\mathbf{x_1}$ and $\mathbf{x_2}$ in both encoding directions are shown in top row with combined uncorrected reconstruction shown on the right. Using the initial B_0 map ($B_{0,initial}$), there were remaining artefacts in the corrected reconstruction ($\mathbf{x_{intial}}$). The proposed joint image and field map estimation framework corrected for most of the artefacts in the final reconstruction ($\mathbf{x_{joint}}$). The model based oracle reconstruction ($\mathbf{x_{oracle}}$) using the true field map (reference B_0) is also shown for comparison.

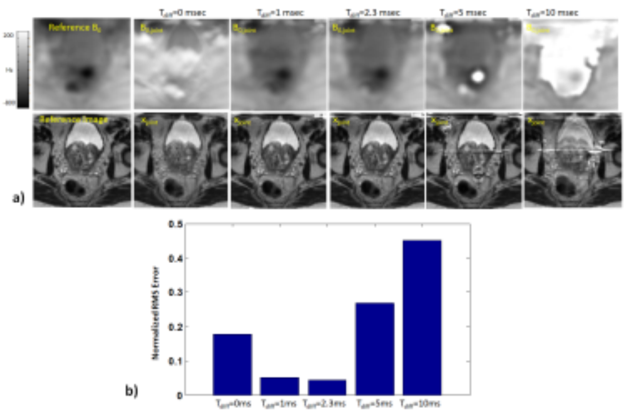

Fig 3: Investigation of effect of varying time shifts (T_{diff}=0-10 msec) on proposed joint image and field map estimation. Reconstructed field maps ($B_{0,joint}$) and images ($\mathbf{x_{joint}}$) for different time shifts are shown in **(a)** with corresponding normalized RMS reconstruction error in **(b)**. Best results were achieved for T_{diff}=1-3 msec.