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DISTORTION CORRECTION IN FETAL EPI USING NON-RIGID REGISTRATION WITH LAPLACIAN CONSTRAINT

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ABSTRACT

We present a novel method for correction of geometric distortions induced by main B0 field in fetal EPI. The method estimates distortion by making the EPI data consistent with reconstructed T2 weighted ssFSE volume. The algorithm consists of two interleaved registration processes: rigid registration of EPI slices with T2 volume to correct for motion; and deformable registration with Laplacian constraint to correct for geometric distortion of EPI slices in a manner consistent with a source free background B0 field. Our results show that the Laplacian constraint significantly improves estimation of the distortion field and EPI volume reconstructed using the proposed method achieves better consistency with T2 weighted volume than EPI volume reconstructed from data corrected by B0 field map.

Index Terms— EPI, fetal imaging, distortion correction

1. INTRODUCTION

Fetal brain imaging is moving from anatomy to connectivity research, requiring advanced neuroimaging modalities such as functional and diffusion MRI. Motion corrected slice-to-volume reconstruction (SVR) techniques are well established for volumetric structural imaging of the fetal brain using single shot Fast Spin Echo (ssFSE) images [1, 2, 3, 4] and related methods have been proposed for diffusion [5, 6, 7] and functional imaging [8]. The diffusion and functional MRI rely on echo planar imaging (EPI), which is highly sensitive to distortion due to static magnetic field (B0) inhomogeneity. However, the correction of spatial distortion resulting from inhomogeneity of the B0 magnetic field has not been included in the previously proposed fetal EPI reconstruction methods. In the case of fetal imaging, inhomogeneity of magnetic field is not always significant because there are no air spaces within the skull and the head is surrounded by amniotic fluid. However, especially in older fetuses, inhomogeneities originating in the mother's body, most notably due to air bubbles, can cause significant local distortion, as shown in Fig. 1, that disrupts the data consistency and the quality of the reconstruction.
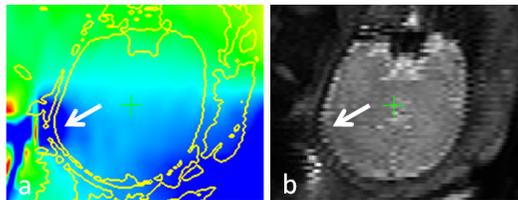
Fig. 1. Variation of B0 field (a) and resulting distortion in transverse cut of fetal brain taken from a stack of coronally acquired EPI (b). The white arrow points to the area of significant local distortion.

A common approach to distortion correction is to acquire B0 field maps [9]. In fetal imaging the B0 inhomogeneity comes mainly from outside of the fetal head, therefore fetal motion does not significantly influence the B0 field. Correction of geometric distortion in the fetus can therefore be performed using a B0 field map [10]. However, the acquisition of B0 field map itself is vulnerable to motion artefacts. In this work we propose an alternative solution to address this problem by including a distortion-correction step in SVR of fetal EPI data. We use a reconstructed T2 weighted volume of the same subject, which is not affected by distortion, as a target to estimate motion and distortion in EPI data. The proposed registration scheme includes a Laplacian constraint, which significantly reduces introduction of registration artefacts and thus plays a key role in estimating plausible B0 field generated by outside sources [11]. We show, that the proposed method achieves better consistency with T2 weighted ssFSE volumes than the B0 field map correction.

2. METHOD

The fetal head is composed of tissues of very similar magnetic susceptibility. There is no air in the frontal sinuses and the skull is not yet widely mineralised. However, outside sources of field variation do exist in proximity of the fetal head, such as gas bubbles in the maternal gut. Significant distortion can therefore be present in EPI of the fetal head, but the B0 field variation, ΔB, is generally smooth in the region of interest and since there are virtually no internal sources, it

obeys Laplacian equation [11]

$$\nabla^2(\Delta B) = 0 \qquad (1)$$

The EPI slices $S_t(y)$ are acquired as regular stacks in scanner coordinate y, but are distorted due to ΔB. As the fetus moves, the fetal head volume, $V(x)$, undergoes a rigid motion, M_t, in time t, such that anatomical location x in the fetal head is related to scanner coordinate y according to:

$$y = M_t x \qquad (2)$$

For each time-point t we can locate the fetal head in the scanner by $V(M_t^{-1}y)$. Due to the B0 field variation ΔB, the fetal head will not appear in the acquired image in location y, but will be shifted by a spatially varying distance $d(y) = (\gamma \cdot \Delta B(y)/bw) \cdot \Delta y$, where γ is gyromagnetic ratio, bw is the bandwidth per pixel and Δy is the pixel width in the direction of the shift. This shift always occurs in the phase-encoding (PE) direction, which can be expressed as a unit vector $\mathbf{p}$. The acquired, distorted, EPI data S_t can thus be related to the moving model of the fetal head by:

$$S_t(y_{it} + d(y_{it}) \cdot \mathbf{p}) = V(M_t^{-1} y_{it}) \qquad (3)$$

where the right side corresponds to the undistorted slices simulated from the aligned model of the fetal head volume V by sampling on the grid y_{it} of the acquired slice S_t.

Motion-corrected T2w ssFSE volumes [4] are not affected by distortions and can be used as the model V. As T2w volumes do not necessarily have the same intensity ranges and contrasts as EPI data, the equality (3) does not hold, but another suitable similarity measure SM can be used to define correspondence between acquired and simulated slices and the distortion can be estimated by optimizing the objective function

$$F(d, M) = \sum_{it} SM(S_t(y_{it} + d(y_{it}) \cdot \mathbf{p}), V(M_t^{-1}y_{it})) \quad (4)$$

To ensure that estimated distortion field d obeys Laplaces equation (1), we introduce a regularisation term $L(d)$, which is implemented as a sum of squared discretized Laplacians of d. The final regularized objective function F_R to be optimized for the estimation of d and M_t can thus be written as

$$F_R(d, M) = F(d, M) + \lambda L(d) \qquad (5)$$

where parameter λ represents the trade-off between the data term F and regularization constraint L.

3. IMPLEMENTATION AND EXPERIMENTS

Optimisation of the objective function (5) consists of two steps: rigid registration of the acquired EPI slices S_t to the model V to estimate motion parameters M_t; and deformable
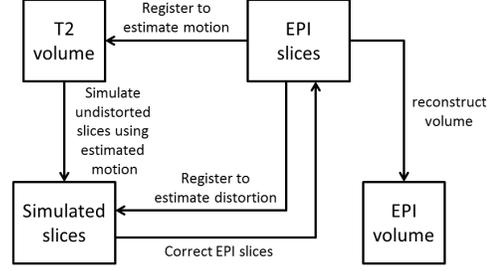

Fig. 2. Summary of the proposed algorithm.

registration of acquired EPI slices S_t to simulated slices $V(M_t^{-1})$ in PE direction only, regularized by the Laplacian constraint, to estimate a smooth distortion field d. This is performed in an iterative manner, and as the iterations progress, motion parameters can be adjusted by registering distortion-corrected rather than original acquired EPI slices. The motion parameters are estimated by rigid registration and distortion by B-spline registration [12] with control point spacing 10mm in the IRTK software package [13] with normalized cross-correlation (NCC) as a similarity measure. During distortion estimation, the parameter λ is first set to a small value to ensure a good fit to the data, and as the iterations progress, this value is progressively increased to ensure a smooth final result and prevent unrealistic deformations caused by differences in intensity profiles of EPI and T2w data. We run the process for a fixed number of iterations, while increasing the number of free motion parameters during iterations until we have one rigid transformation per slice. After the process converges, the EPI volume is reconstructed using our previously proposed method [4]. The algorithm is illustrated in Fig. 2.

It should be noted, that there is not a unique solution for optimal motion and distortion parameters: translation of the slices in the PE direction can be interpreted either as a motion or a distortion. The algorithm is thus capable of correctly estimating the undistorted slices, but not necessarily the true motion and distortion parameters.

We therefore evaluated the accuracy of the distortion field estimation with fixed motion parameters, which were estimated by aligning EPI slices corrected by acquired field map to the ssFSE T2w volume (experiments 1 and 2 in Table 1). Simulated slices were then calculated using the fixed motion

Experiment	1	2	3
distorted slices	simulated	acquired	acquired
motion parameters	fixed	fixed	estimated
evaluation	smoothed field map	acquired field map	ssFSE T2w volume

Table 1. Experiments to evaluate the distortion estimation

parameters. In the first experiment we smoothed the acquired field map to make sure it obeys Laplace's equation and used it to distort the simulated slices. The distortion field was then estimated by registering simulated distorted slices to simulated undistorted slices. The estimated fieldmap was compared to the applied fieldmap. In the second experiment the distortion field was estimated by registration of acquired data to undistored simulated data and the resulting distortion field was compared to the original acquired fieldmap.

In the third experiment (experiment 3 in Table 1) we performed the full algorithm with simulataneous estimation of motion and distortion using acquired data. As we were not able to evaluate the accuracy of distortion field itself, we instead compared the reconstructed EPI volume corrected for motion and distortion to ssFSE T2w volume. The similarity was quantified using NCC, which was calculated locally to account for differences in acquisition protocols of ssFSE and EPI images and B1 field induced intensity inhomogeneity. For that we normalized both images with local mean and variance calculated with Gaussian kernel $\sigma = 20$mm.

4. RESULTS

The proposed distortion correction and reconstruction method was applied to nine spin-echo diffusion scans of fetal head with diffusion gradients set to zero (dMRI b=0, TE 121ms, TR 8500ms, FoV 290x290x128mm^3, voxel size 2.3x2.3x3.5mm^3, slice overlap 1.75mm), each consisting of four stacks of slices acquired on the same grid. T2 weighted volumes reconstructed from ssFSE slices [4] and acquired B0 field maps (TE1 4.6ms, TE2 9.2ms; TR 10ms, Flip Angle 10°, voxel size 2.27x2.27x10mm^3, FoV 400x400x150mm^3) were available for all the scans.

In the experimets with fixed motion (see Table 1), the registration was performed with and without the Laplacian constraint. The comparison between simulated/acquired and estimated field map is presented in Table 2. In case of simulated EPI we obtained average error of 0.19mm with B-spline registration only and Laplacian constraint improved the average error to 0.17mm which was statistically significant ($p < 2{\cdot}10^{-5}$). In case of acquired EPI, differences in intensity profiles of acquired and simulated slices resulted in artefacts when using B-spline registration, see Fig. 3c, but Laplacian constraint helped to descrease the average error from 0.72 to 0.54 mm ($p < 4 \cdot 10^{-4}$). The example of the acquired and estimated field map is presented in Fig. 3.

Experiment	EPI/field map	B-spline	Laplacian
1	simulated	0.19 ± 0.06	0.17 ± 0.06
2	acquired	0.72 ± 0.46	0.54 ± 0.34

Table 2. Average error and standard deviation between simulated/acquired and estimated field map given in mm.
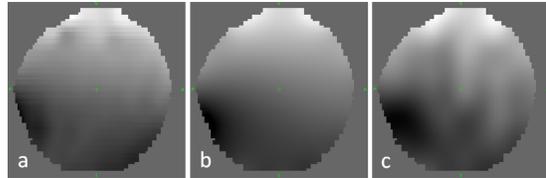

Fig. 3. Comparision of acquired and estimated fieldmaps: (a) Acquired fieldmap; (b) estimated fieldmap with the Laplacian constraint; (c) estimated fieldmap without the Laplacian constraint. Note the artefacts in (c) when the Laplacian constraint is not used.

In the third experiment we performed simultaneous estimation of motion and distortion from acquired EPI, followed by reconstruction of EPI volume [4]. For comparison we also reconstructed EPI volumes from uncorrected EPI slices and slices corrected using acquired field maps, without estimating the distortion. The results presented in Table 3 show, that both field map correction and correction using our proposed method result in significant improvement ($p < 0.0005$) in similarity with T2 volume. Additionally, our proposed method achieved significantly better consistency with T2 weighted volume than the fieldmap correction ($p = 0.003$), with increase in local NCC in all cases. We present the comparison of the four reconstructed volumes for scan 1 in Fig. 4

	No correction	field map	proposed
Scan 1	0.78	0.82	0.83
Scan 2	0.77	0.82	0.83
Scan 3	0.75	0.80	0.80
Scan 4	0.66	0.69	0.70
Scan 5	0.65	0.69	0.71
Scan 6	0.68	0.75	0.76
Scan 7	0.64	0.76	0.80
Scan 8	0.76	0.79	0.81
Scan 9	0.73	0.78	0.82
Average	0.71	0.77	0.79

Table 3. Comparison of reconstructed EPI image with ssFSE T2 volume using local NCC, without distortion correction, and with distortion correction using either acquired B0 field map or the proposed method.

5. CONCLUSION

In this paper we presented a novel method for distortion correction of fetal EPI based on registration with undistored reconstructed ssFSE volume. Our results show that this method provides a viable alternative to correction using acquired B0 field maps, especially in cases when B0 field map is corrupted
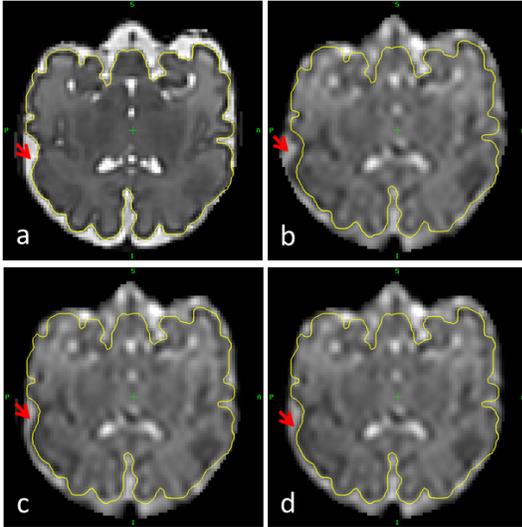
Fig. 4. Comparison of reconstructed ssFSE and EPI volumes: (a) ssFSE T2w volume; EPI volume with (b) no distortion correction, (c) correction using acquired fieldmap, (d) correction using proposed method. Yellow line shows the outline of the brain in ssFSE T2w volume. Reconstructed EPI using the proposed method shows the best consistency with ssFSE T2w volume (see red arrows).

by fetal or maternal motion or when acquisition time is limited.

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