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COMPARISON BETWEEN SYNb0-DISCO AND FIELDMAP-BASED METHODS TO CORRECT FOR DISTORTION ARTIFACTS IN DIFFUSION MRI

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ABSTRACT

Diffusion-weighted images acquired with echo planar imaging (EPI) are sensitive to static magnetic field inhomogeneities that can cause distortion artifacts in the phase encoding direction. These artifacts are detrimental for the analyses and several methods have been developed to correct them. Some methods require the acquisition of a dedicated B_0 map like the fieldmap-based method and the state-of-the-art "blip-up/blip-down" method. Others do not, like methods using non-rigid registration to a structural image, but they show weaker results. Recently, a method called Synthesized b_0 Distortion Correction (Synb0-DisCo) that uses deep learning to perform corrections without additional data (Schilling et al. 2020) has been developed. This study evaluates the Synb0-DisCo algorithm against the other mentioned methods. We performed comparisons on the displacement fields, the $b = 0$ (diffusion-unweighted) images, and between the $b = 0$ images and the T1-weighted images; using mono-centric data from 50 healthy subjects. We found that, in this context, the methods using fieldmaps outperform the Synb0-DisCo method in most respects.

Index Terms— diffusion MRI, susceptibility artifacts, Synb0, fieldmap

1. INTRODUCTION

Diffusion-weighted Magnetic Resonance Imaging is a non-invasive imaging technique that is sensitive to the movement of water molecules within the brain. It allows us to study, in vivo, the organization of the white matter and the microstructure of the brain. To be able to obtain such information, we generally perform Echo Planar Imaging (EPI) which is sensitive to local inhomogeneities of the main magnetic field B_0 . This sensitivity results in geometric distortions in the phase encoding (PE) direction that are mainly localized in areas close to the tissue-air interfaces, such as frontal sinuses and the ear canals, and are detrimental to the analyses. Indeed, they depend on several factors such as the anatomy of the subject and are therefore specific to each imaging session. This leads to misalignment between modalities and may impact accuracy in the affected regions.

Many processing techniques have been developed to correct these distortions. We can separate them into two groups: methods that require additional B_0 -mapping data, and methods that do not. In the first group, we can mention the fieldmap method: a B_0 map is reconstructed from double-echo 3D gradient echo (GRE) images, which can then be used to estimate the deformations induced by B_0 heterogeneity and therefore correct for distortion artifacts. More recently, so-called "blip-up/blip-down" techniques, such as the FSL TOPUP algorithm, propose to acquire at least one image in the reverse PE direction to estimate the deformations undergone by the images and correct the distortion artifacts; they are considered state of the art, since they have been shown to be the most efficient on real and simulated data [1]. In the second group, a traditional approach is to non-rigidly register the $b = 0$ (diffusion-unweighted) image to a structural image such as the T1-weighted image, which is an undistorted anatomical reference. However, this method was shown to be less efficient than both B_0 -mapping based methods [1]. Recently, a technique called Synthesized b_0 Distortion Correction (Synb0-DisCo) was developed to perform distortion artifact correction without acquiring additional images [2]. It uses deep learning techniques to synthesize an undistorted $b = 0$ volume from the distorted $b = 0$ image and the T1-weighted image. This volume is then given to the TOPUP algorithm with the acquired distorted $b = 0$ image and custom parameters to perform the correction. Thus, this method allows the state-of-the-art algorithm to be used without having acquired the blip-down images. The authors of the Synb0 method showed better results with this method than with the traditional T1-registration method [2].

To the best of our knowledge, no comparison between the fieldmap method and the Synb0-DisCo method has been published. Therefore, we sought to answer the following questions: does the Synb0-DisCo method perform better than the fieldmap method? Is it advantageous to use this new technique when fieldmaps have been acquired? In order to answer these questions, we compared the performance of Synb0-DisCo with the results obtained with a registration method and the fieldmap method on data from 50 cognitively healthy subjects and using blip-up/blip-down correction as reference.

2. METHODS

2.1. Participants and acquisition

For this study, we used data from 50 subjects of the SENIOR cohort, acquired at NeuroSpin [3] (CEA Paris-Saclay, France) and gathering cognitively healthy volunteers. The mean age is 65.5 years (range 55–78 years). All participants provided informed written consent for their participation.

MRI data was acquired using a 3T Siemens Magnetom Prisma scanner with a 20-channel head coil. For each subject, 3D T1-weighted images were acquired with a MPRAGE sequence (voxel size = 1 mm isotropic, TE = 2.98 ms, TR = 2300 ms, TI = 900 ms, flip angle = 9°) and diffusion images were acquired using a single-shot EPI sequence (TE = 77 ms, TR = 7000 ms, voxel size = 1.3 mm isotropic, acquisition matrix = 184 × 184, GRAPPA acceleration = 2, partial Fourier factor = 0.625). Each diffusion acquisition comprised 3 shells of diffusion with b -values of 200, 1700 and 3200 s/mm² with 60 directions per shell. Moreover, each shell is preceded by two $b = 0$ volumes with respectively antero-posterior PE (blip-up) and postero-anterior PE (blip-down). These acquisition parameters are similar to those used for the training of the Synb0-DisCo algorithm. Double-echo 3D GRE images were also acquired (Δ TE = 2.46 ms, TR = 800 ms, voxel size = 3 mm isotropic).

2.2. Image Processing

Non-corrected (NC) images All images were first pre-processed using the MRtrix3’s tool *dwidenoise* ([4]). The $b = 0$ images obtained after this step are the images used as inputs for each following distortion correction method.

TOPUP method (reference) As the blip-up/blip-down method is the commonly accepted state-of-the-art method, we decided to use it as a reference. We used the TOPUP tool from FSL ([5]) on all six $b = 0$ images with default parameters.

For this method and the others, the correction was applied on the first blip-up $b = 0$ image only, using Jacobian modulation to restore the intensities on the corrected image.

Registration-to-T1 (Reg T1w) method This method performs distortion correction by registering the $b = 0$ image onto a structural image. We used the T1-weighted image and the algorithm implemented in the BrainSuite software toolkit with default settings ([6]). This algorithm constrains the deformation field along the PE axis.

Fieldmap (FM) method Fieldmap-based methods use a B_0 fieldmap obtained from double-echo GRE images to estimate the deformation field related to field heterogeneity. For our study, we first brain-extracted the first magnitude GRE image and eroded the mask by one voxel to remove noise at the edge of the brain. We then estimated the fieldmap in the eroded mask with the *fsl_prepare_fieldmap* algorithm from FSL. Next, in order to remove discontinuities at the edge of

the mask, we extrapolated the fieldmap by mean-dilating the non-zero voxels until the entire field of view was covered. Finally, we used FUGUE from FSL ([7]) to unwarp the $b = 0$ image. During this step, we smoothed the fieldmap using a 3D Gaussian kernel with a width of 1 voxel and we applied Jacobian modulation.

Synb0 method The last method consists of using the Synb0-DisCo algorithm ([2], version 3.0.0) as it is implemented in the Singularity container, with default parameters. We applied the resulting displacement using Jacobian modulation.

2.3. Comparison metrics

We performed comparisons in order to evaluate the ability of each method to 1) correct brain structures’ positions with comparisons of the displacement fields, and comparisons of the undistorted images with the T1-weighted image; and 2) recover signal values, with comparisons between the $b = 0$ images.

We first calculated masks on the T1-weighted images with the HD-BET algorithm [8]. To include edge effects, we dilated those masks by 7 mm. We then registered each $b = 0$ volume to the T1-weighted image with the FSL *epi_reg* function (which uses Boundary-Based Registration, [9]). The inverse transformations can be used to obtain the dilated brain masks in each $b = 0$ space.

We give the root mean square (RMS) for an image Y :

$$\text{RMS}(Y) = \sqrt{\sum_k y_k^2/n} \quad (1)$$

Displacement field comparisons For each correction method, we masked the displacement fields with the dilated brain mask in the uncorrected $b = 0$ volume space.

We computed joint histograms between the displacement values obtained with each method and the reference TOPUP method, concatenating the values obtained for all subjects.

We then centered the displacement fields by subtracting from each field the corresponding mean displacement value, and we calculated the RMS error (RMSE) between the centered displacement field obtained with each method (F) and that obtained with TOPUP (\hat{F}): $\text{RMSE}_{df} = \text{RMS}(F - \hat{F})$.

Comparisons to the T1-weighted image We used the $b = 0$ volumes previously rigidly registered to the T1-weighted image that we masked with the dilated brain mask in the T1-weighted space. We then calculated the Normalized Mutual Information (NMI) between each $b = 0$ image and the T1-weighted image as defined by Studholme et al. ([10]):

$$\text{NMI}(X; Y) = \frac{H(X) + H(Y)}{H(X, Y)} \quad (2)$$

where $H(X)$ is the marginal entropy of X and $H(X, Y)$ is the joint entropy. We used the same binning for the histograms of all methods to ensure comparability.

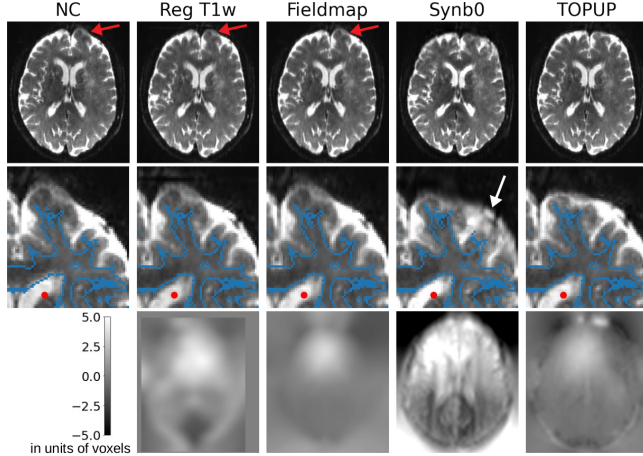


Fig. 1. Results obtained for a representative slice with each distortion correction method. Top row: $b = 0$ volume corrected by each method; middle row: zoom of the first row images registered to the T1-weighted image; bottom row: displacement fields obtained with each method. The red dot is placed at the same coordinates on each image. Blue lines: segmentation of the gray-white interface performed on the T1-weighted image

Comparisons of $b = 0$ images We used the $b = 0$ volumes previously rigidly registered that we masked with the dilated brain mask in the T1-weighted space.

We calculated the RMSE between the signal values of each distortion correction method $b = 0$ volume (I) and the TOPUP-corrected $b = 0$ image (\hat{I}). We normalized this RMSE value by the RMS signal intensity of the TOPUP-corrected image ($RMS(\hat{I})$):

$$RMSE_{b0} = \frac{RMS(I - \hat{I})}{RMS(\hat{I})} \quad (3)$$

Statistics For each comparison metric, we tested the difference between the FM method and the Synb0 method with a one-sided Wilcoxon signed-rank test on the metric’s distribution over the 50 subjects. The significance is tested at $p < 0.001$ (***)

3. RESULTS

Figure 1 shows the results of each distortion correction method on a representative slice. The red dot is at the same coordinates on each image of the second row so we can compare the positions of the structures.

On the first row, the red arrows point at strong local distortions that are present in the NC image. They are also present in the Reg T1w and FM images but were efficiently corrected by the Synb0 and TOPUP methods. On the second row, the blue line represents the segmentation of the gray-white interface performed on the T1-weighted image and is used as the reference position of the cerebral structures. In this context, we can see that the anterior edge of the anterior horn of the

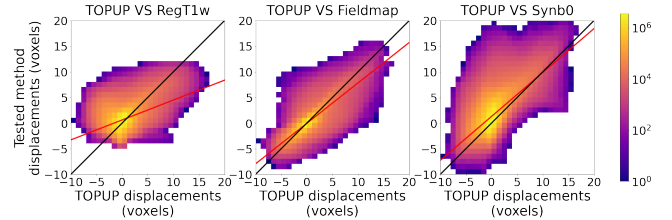


Fig. 2. Joint histograms between the displacement fields for the Reg T1w method (left), the FM method (middle) and the Synb0 method (right), and the TOPUP displacement field, computed using all 50 subjects. Black line: $y = x$ line, red line: linear regression.

right lateral ventricle does not fit well within the blue line on the NC image, as the distortion globally dilates the frontal lobe. On the other images, we can note that this effect is corrected by all methods. Besides, we can note that, while the ventricle fits well within the blue line, the red dot lays at the edge of the ventricle for the Synb0 method whereas it is inside this structure with the other methods, indicating that the Synb0 method compressed the ventricle a little. Moreover, the white arrow shows reconstruction artifacts (blurring) that appear with the Synb0 method. On the displacement fields, we can see a strong displacement at the frontal pole on the TOPUP method, which corresponds to the correction of the local distortions pointed to by the red arrows. This displacement is also present for the Synb0 method but absent for the other two. We also note that the displacement field obtained with the Synb0 method features higher displacement values and much more spatial heterogeneity compared to other methods, which is consistent with the compressed ventricle and the reconstruction artifact.

Displacement field comparisons Figure 2 shows the joint histograms of the displacement fields. This allows us to compare the dispersion of the displacements estimated with each correction method compared to the TOPUP method.

We observe that the Reg T1w method presents a slope much lower than unity for the linear regression (red line). Indeed, we can see that this method generally underestimates the displacements. The joint histogram for the FM method shows less dispersion than the other two, and the linear regression is quite close to the $y = x$ black line. Finally, we can see for the Synb0 method that, in general, the stronger intensities are quite well aligned with the diagonal — albeit with an offset of around 1 voxel, which is not detrimental as we are interested in relative displacements. On average, the estimation performed by this method is close to the TOPUP method estimation as we can see the linear regression presents a slope close to unity. On the other hand, we note that this estimation is noisy: there is a large dispersion especially around the $x = 0$ line, indicating that the Synb0 method estimated displacements of several voxels where the TOPUP method estimated essentially zero.

We obtained the following median \pm interquartile range values for the $RMSE_{df}$ between each method’s centered

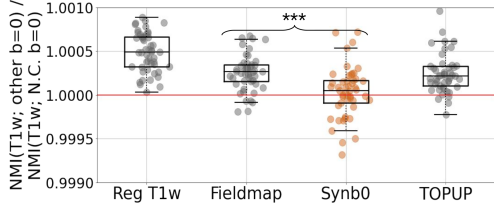


Fig. 3. Ratio between the NMI (Equation 2) calculated between T1-weighted image and $b = 0$ volumes obtained with each correction method and the NMI calculated between T1-weighted image and the NC $b = 0$ volume across the 50 subjects.

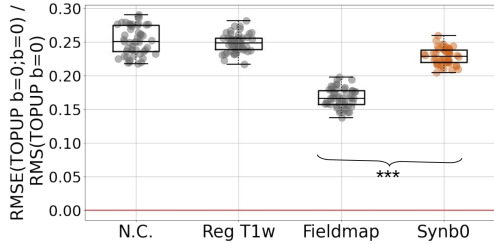


Fig. 4. Distribution of $RMSE_{b0}$ (Equation 3) across the 50 subjects.

displacement fields and the TOPUP centered displacement field calculated across the 50 subjects: NC, 1.64 ± 0.22 ; Reg T1w, 1.66 ± 0.23 ; FM, 0.89 ± 0.16 ; Synb0, 1.82 ± 0.27 (in unit of voxels). We note that the FM method presents the best concordance with TOPUP, and that the Synb0 method presents the worst. The Wilcoxon test showed that the results obtained for the FM method are significantly lower than the Synb0 results, meaning that the FM method performed significantly better than Synb0.

Comparisons to the T1-weighted image Figure 3 shows the NMI calculated between the T1-weighted image and the $b = 0$ volume obtained with each distortion correction method, normalized by the NMI calculated between the T1-weighted image and the NC $b = 0$ volume, across the 50 subjects (higher is the best).

For all methods, we see that the median value is higher than 1, meaning that all methods improve alignment to the T1-weighted image compared to the NC image. Notably, the Reg T1w method always improves this registration, which is consistent since this correction method works by optimizing mutual information. The FM method and the TOPUP method show comparable results, and the Synb0 method performs only slightly better than the NC image on average. The Wilcoxon test showed that the FM method again performed significantly better than the Synb0 method.

Comparisons of $b = 0$ images Figure 4 shows the results of the normalized $RMSE_{b0}$ calculated across the 50 subjects between the $b = 0$ volumes obtained with each distortion correction method and the TOPUP $b = 0$ volume.

We can see that the best $RMSE_{b0}$ values are obtained with the FM method. The Synb0 method shows better results than the Reg T1w method but worse than the FM method. The Wilcoxon test showed that the FM method again performed

significantly better than Synb0.

4. DISCUSSION

In this study, we have compared different distortion correction methods for EPI-based diffusion MRI images, using the state-of-the-art blip-up/blip-down method as a reference. Our results show that the fieldmap method performs a better correction of the distortion artifacts than the Synb0 method.

On average, the displacements estimated by the fieldmap method and the Synb0 method are both close to the displacements estimated by the TOPUP method (i.e. on Figure 2, the slopes of the linear regressions are both close to 1). However, we also saw that for all quantitative comparisons, the fieldmap method performs significantly better than the Synb0 method. This is explained by the fact that the Synb0 method performs a noisy estimation of the displacements: the displacement values obtained with this method are much more dispersed than the values obtained with other methods. Therefore the Synb0 method sometimes adds some displacements where it should not, as we saw with the compressed ventricle and the reconstruction artifacts (Figure 1). This is particularly highlighted by the $RMSE_{df}$ values calculated on the displacement fields. On the other hand, this dispersion might sometimes enable the Synb0 method to correct very local strong distortions, like the distortions appearing at the edge of the frontal pole.

As for the evaluation of the performance obtained with the other methods, we found, consistently with previous findings [1], that the fieldmap method in general performs better than the T1-registration method. Results are less clear concerning the comparison between the Synb0 method and the T1-registration method: Synb0 performs a good estimation on average but introduces noise, whereas T1-registration tends to underestimate the displacements.

It should be noted that results may vary according to the quality and resolution of the data. In the original Synb0 paper [2], tests performed on the database that is most similar to ours (HCP) showed the least improvement with Synb0. Therefore, our results may not generalize to databases with very different acquisition parameters. In a further study, it could be interesting to perform the analysis on simulated data with various acquisition parameters to test this hypothesis. This type of analysis could also enable to compare the results with a ground truth instead of using the TOPUP method as reference. Finally, it would also be interesting to evaluate the influence of each method on diffusion metrics such as Fractional Anisotropy.

To conclude, we showed that, although the Synb0 method presents better visual results for the correction of strong local distortions, it is more advantageous to use the fieldmap method to perform the correction if the double-echo GRE images are available, even when this fieldmap is acquired with limited spatial resolution.

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7. CONFLICTS OF INTEREST

The authors have no conflicts of interest to disclose.

8. COMPLIANCE WITH ETHICAL STANDARDS

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee.