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# Evaluation of Echo Planar Imaging (EPI) Distortion Correction using Synb0-DisCo and Reversed Phase Encoding Acquisition

Alejandro Garma-Oehmichen[1], Kathya P. Acuña-Luna[1], and Alejandro Santos-Díaz[1,2]

*Abstract*— **Diffusion weighted imaging is a widely used imaging technique for the assessment of white matter using tractography. Nevertheless, due to practical constraints such as limited acquisition times, differences in scanning methods and physical artifacts, these images must be processed by image correction algorithms in order to produce reliable results. State-of-the art susceptibility correction algorithms such as FSL's TOPUP algorithm typically requires at least two images acquired with no diffusion encoding (b=0) in the regular and reverse phase encoding directions, commonly known as double-blip acquisitions, in order to calculate an undistorted volume. Since not all imaging protocols include a double-blip acquisition, they cannot take advantage of these state-of-the-art distortion correction algorithms. A new approach based on a Synthetic b-0 Distortion Correction (Synb0-DisCo) has been tested with favourable results. Synb0-DisCo has proven to reduce variation in diffusion modeling creating a synthetic b-0 image to complement the single phase encoding b0 image. In this study, we aim to assess if there are any significant differences in Synb0-DisCo's efficacy resulting from different b-values. To observe critical metrics in the performance of susceptibility correction algorithms we use a 20 healthy subject database from project larynx to create four image sets containing: raw images, single phase encoding eddy correction, double phase encoding eddy correction and one single phase encoding plus a synthetic Synb0-DisCo image eddy correction. From this four image sets we then obtained the mean squared error (MSE) and mutual information (MI). We observed a diminished mean in the MSE, along a smaller dispersion, in the raw image set (Mean: 0.0306; C.I.[0.0369,0.024]) in comparison to the Synb0 image set (Mean: 0.0130; C.I.[0.0194, 0.0067]) We also observe a shift in the MSE depending on the b-value, where b-0 incurs the least MSE which does not occur in b-1000 and b-2000. This effect is lessened in the Synb0 image set. In absence of double phase encoding b-0 image, Synb0-DisCo proves to be a reliable algorithm to improve susceptibility distortion correction.**

## I. INTRODUCTION

Diffusion weighted imaging (DWI) is a non-invasive method that allows the visualization of diffusion movement of water molecules in vivo. This type of image provides important information about the tissue microstructure and maps the overall direction of axons in the white matter. Most DWI images are acquired using echo-planar imaging (EPI). The downside of this type of acquisition is that these sequences are susceptible to geometric and intensity distortions caused by magnetic field inhomogeneities, that in addition to low bandwidth in the phase-encode (PE) direction, causes spatial distortion along the PE axis. These distortions can significantly impact the accuracy of the analysis in affected regions and can generate a misalignment with complementary. [1].

Multiple strategies have been developed in order to correct EPI distortions. Methods such as correction by b0 mapping, point spread function estimation or image registration to an anatomical target [2], [3], [4], [5], [6] can be implemented in the data processing stage. Unfortunately, these methods suffer from limitations yielding to the requirement of further optimization metrics or pre-processing steps. Further development in the field of EPI distortion correction has landed with the current state of the art: the "blip-up/blip-down" acquisition method [7]. This method corrects the distortions by merging and warping two reversed phase encoded b0 images into a single non-distorted b0 volume. This algorithm is available as EDDY in the FSL software package. Another algorithm commonly used with EDDY is TOPUP, which estimates the un-warped images independently along the PE direction by normalizing the geometric mean.

However, not every imaging protocol includes reversed phase encoding acquisition images and therefore they cannot benefit from the state-of-the-art correction that EDDY and other preprocessing algorithms offer. Furthermore, many old datasets were not collected using this sequence and adoption of this practice in research and clinical settings is limited due to unfamiliarity with the methods and outdated software. The recent development of the Synthesized b0 Distortion Correction (Synb0 DisCo) [8] is able to address such limitations as it uses a machine learning framework to create a synthetic b0 undistorted image. This is accomplished by a U-net neural network using as inputs the distorted b0 image and an anatomical T1 weighted image. Thus, this approach allows the implementation of advanced distortion corrections and modern processing pipelines on most existing available diffusion imaging datasets. The purpose of this study is to evaluate the performance of EPI distortion correction using Synb0-DisCo with multiple b-values.

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[1]Alejandro Garma-Oehmichen is with the School of Engineering and Science, at Tecnologico de Monterrey, CDMX, Mexico. Email: a01333481@itesm.mx

[1]Kathya P. Acuña-Luna is with the School of Engineering and Science, at Tecnologico de Monterrey, CDMX, Mexico. Email: a01187885@itesm.mx

[1,2]Alejandro Santos-Diaz is with the School of Engineering and Science and the School of Medicine and Health Sciences, both at Tecnologico de Monterrey, CDMX, Mexico. Email: alejandro.santos@tec.mx

## II. METHODOLOGY

### A. Population Study

The subject database, consisting of 20 healthy subjects, was obtained from the database Project Larynx version 2.1.0, from OpenNeuro with accession number ds002634. The information was anonymized before being uploaded. Project Larynx was approved by the Central University Research Ethics Committee (CUREC, R55787/RE001) in accordance with the regulatory standards of the Code of Ethics of the World Medical Association (Declaration of Helsinki). All subjects gave informed consent to their participation and were monetarily compensated for their participation. Further details on the dataset are found in [9]

### B. MRI data acquisition

MRI data was obtained at the Oxford Centre for Human Brain Activity (OHBA) using a 3-T Siemens Prisma scanner with a 32-channel head coil. A structural image of the whole brain was acquired; a T1w image (MPRAGE sequence; 1 mm3 isotropic resolution, TR = 1900 ms, TE = 3.97 ms, TI = 905 ms, 8° flip angle, bandwidth = 200 Hz/pixel, echo spacing = 9.2 ms, FOV = 192 × 192 × 174 mm3)

Diffusion acquisition was acquired using a multiband echo-planar imaging sequence with FOV = 104x104x72, multiband accelerator factor = 3, TR = 3600 ms, TE = 92ms. A total of 108 directions were acquired, 50 of them b = 1000, 50 for b = 2000 and 8 for b = 0. Of the eight b0 images, five b-0 images were obtained in a AP direction while the additional three b-0 images were obtained in a PA direction.

### C. Image processing

The software used were: Mrtrix3 for preprocessing, Synb0-Disco for creating the synthetic PA image, and FSL for Eddy's distortion removal. As our first step after acquisition, all images were pre-processed. For this, we used the Mrtrix3 software for the denoising and unringing algorithms [10]. From the original database, we created four subsets. The first set, the "raw" set, was the images after preprocessing. The next processing step involved FSL's TOPUP and EDDY tools to obtain distortion corrected images. The second set was processed using just one image direction (AP) creating the "no-blip" image set, while the third set was processed using both phase-encoded directions, blip-up blip-down set with AP>>PA b-0 sequence, henceforth called "blip" set. Finally, a synthetic b0 image was generated with Synb0-Disco, substituting the PA direction used in FSL's EDDY, this became our fourth image set, named "synb0". This resulted in four final images for each subject, one without Eddy correction, one corrected with a single phase encoding direction b0 image, one corrected with both phase encoding directions b0 images and another corrected with one Synb0-DisCo synthetic image and one phase encoding direction b0 image.

Fig. 1. The left image shows a subject from the first with a single phase direction AP, significant distortion on the frontal lobe can be observed. The right shows the corresponding image from the fourth data-set, which is generated by Synb0-Disco.

After acquiring the four image sets, a binary mask was created from any valid diffusion data in any given voxel. Then, the images were normalized in a [0-1] range. After this, the mean value for each image set and for each shell was obtained. To exemplify this, each patient was compromised of four image sets: Raw set, No-blip set, Blip set, and Synb0 set. Each set was compromised of 5 images: A binary mask, a mean image, a b-0 mean, b-1000 mean, and b-2000 mean.

To compare these images, the mean squared error and mutual information were obtained. Both of these metrics were calculated for the mean and the b-value shells; This in order to determine if any of these variations affect the efficacy of Synb0-Disco. Fig. 1 shows an example of a distorted and synthetic b-0 images.

### D. Data comparison

A script was written in order to compare the four resulting image sets along its shells, and therefore to observe how well Synb0-Disco performed against alternative methods. For the mean square error (MSE), eq(1) is employed.

$$MSE = \sum (y_i - \hat{y_i})^2/n \tag{1}$$

Where "y" stands for the Blip image, as is given as the gold standard in this paper. For our estimator, "ŷ", stands for the raw, no-blip or synb0-Disco image. The denominator "n" stands for all voxels included in both the y and ŷ image that contain viable diffusion data. We evaluated the MSE for all images with all b-value means.

For Mutual Information (MI), the images were condensed in probability mass functions (PMF) to observe the depending information between two random variables. The following eq(2) was used.

$$MI = \sum_{y \in Y} \sum_{x \in X} p(x,y) log(\frac{p(x,y)(x,y)}{p_X(x) p_Y(y)}) \tag{2}$$

Where pX(x) is the PMF of image X and p(x,y) is the joint PMF of the image X and Y. In mutual information, a higher score indicates a higher relationship between two images, while a lower score indicates the opposite. We envision that distortions will alter MI scores, making images more or less similar. For every subject and for every

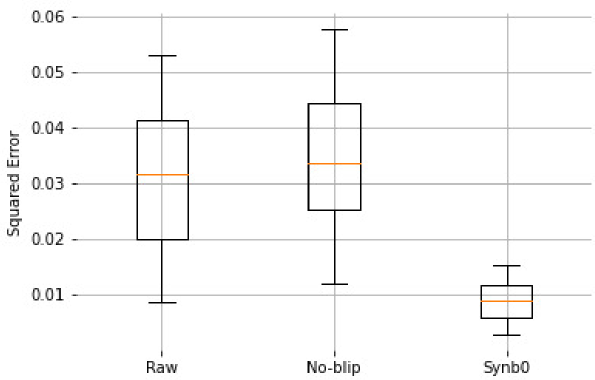


Fig. 2. Squared error boxplots detailing the values obtained from the mean image across the 20 subjects; Comparison between Raw, No-blip and Synb0-Disco images.

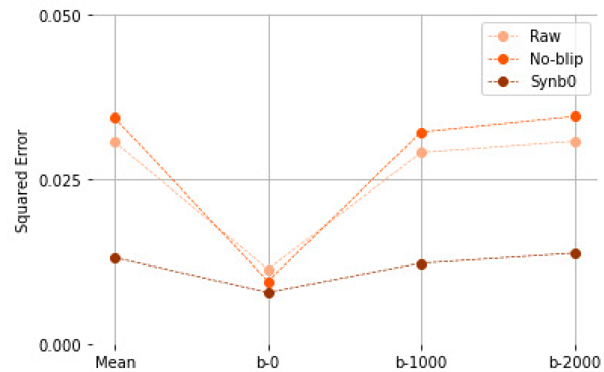


Fig. 3. Mean squared error comparison against double-phase encoded images for every b-value and mean images.

b-value, three distinct data set comparisons were obtained: Double-blip vs. No-blip, Double-blip vs. Synb0-Disco, and Synb0-Disco vs. No-blip.

## III. RESULTS

MSE results allow us to observe the difference between the "gold standard", in this case the double phase enconded images ("blip"), and the other data sets. In Fig. 2 we can observe the average value and the dispersion of different data sets. For the Raw and No-blip image sets, the MSE remained almost constant. There is a slight increase in the mean and in the dispersion, indicating that after the Raw image is processed through TOPUP/EDDY, the difference between the correction with only one phase encoding increases in comparison with both phase encodings. Nonetheless, these results aren't significant, and can be attributed to noise.

For the Synb0-Disco set, a significant drop in MSE occurs, reflected in the smaller value for the median and the more compact dispersion. This result in the MSE implies that the difference between the diffusion data in the Blip image set and the Synb0 image set is less than the difference between the Blip set and the Raw, No-blip set. This also suggests that Synb0-Disco can generate reliable synthetic images for correct Eddy current correction through FSL tools, and that the result will be closer to what an original blip-up, blip-down sequence would have achieved comparing with a No-blip image. In Fig 2, the MSE values are: Raw mean MSE is: 0.0306 with 95% C.I.[0.0369, 0.0243]; No-blip mean MSE is: 0.0343 with 95% C.I.[0.0405, 0.0281] ; Synb0 mean MSE is: 0.0130 with 95 % C.I.[0.01940, 0.0067]

In fig (3), the mean value across all 20 subjects was obtained in accordance to its mean image and its mean shell values. Here a general trend can be observed. As the b-value increases, so does the MSE. This occurs due to the Signal to Noise Ratio (SNR) diminishing as the b value increases. As the gradient amplitude increases to accommodate a higher b-value, the SNR diminishes. This translates to an MSE increase in the Eddy corrections between the lower amplitude shells to the higher amplitude shells. TOPUP and EDDY tools generate an affine transformation between the two phase encoding images to generate a new corrected b-0 image. We hypothesize that the loss of SNR in higher shells cause a greater deviation when comparing a No-blip/Raw with a Blip image. Accordingly, Synb0 images also suffer an increase in MSE in higher shells, but at a diminished rate. The MSE values for the mean b-value, b0, b1000 and b2000, for the Raw set were [0.0306, 0.0113, 0.0290, 0.030] ; For No-blip set were [0.0343, 0.0094, 0.0322, 0.0346] ; For the Synb0 set were [0.0130, 0.0077, 0.0122, 0.0137].

For the mutual information (MI), we observed the interaction between the sets of Blip, No-blip and Synb0 at the mean, b-0, b-1000 and b-2000 images. In Fig4 each coloured bar represents a comparison between two sets and each cluster of bars the type of image. The error bars represent 1 standard deviation for each image.

A general trend is observed in all types of images, the MI score was higher for Synb0 & No-blip than Blip & No-blip. This indicates that given the Eddy correction, Synb0 images remain more similar to the No-blip image in comparison with the Blip image. We can also take into account that the MI score for Synb0 & Blip has a low amplitude in comparison with Synb0 & No-blip. If the correction for Eddy currents generated with the synthetic image were to be identical to using two-phase encoding directions, the expected MI would be of a higher amplitude. What we observe is contrary to these affirmations. Considering the observed data, Synb0 images offer a resulting image that retains a more similar architectural structure than both phase encoding directions do.

One must also take into account that these values are

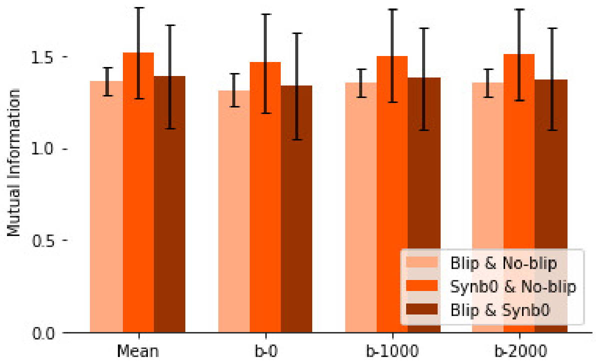


Fig. 4. Mutual information comparison for different b-values.

only representative as a comparison between themselves, and are relative to each other. What may look like a steep difference in amplitudes may differ from real changes in the observed images.

## IV. DISCUSSION

The results obtained confirm that Synb0-Disco emulates a reversed phase encoded image to complement a no-blip acquisition and it's a considerable improvement over pipelines using only one phase-encoding direction.

The results from MSE indicates that the distortion of single phase encoding images lessens with the usage of the aforementioned algorithm. Though the change in image simmilartity, as measured by the MI, is less in the case of the Synb0 image set than the Blip image set, suggesting that the structural change after TOPUP and EDDY may differ in some sort when comparing a double encoding corrected image.

Confirming the reliability and accuracy of Synb0-Disco against the usage of no-blip and double-blip images for different b-values is a valuable asset since it allows researchers and physicians to use a wider variety of datasets with confidence in the quality of the results obtained. This allows the usage of state-of the art methods in existing datasets, oftentimes sparing the need of using smaller, less-well fitted datasets or needing to acquire new images, saving time and effort in many cases.

## APPENDIX

The medical images used in this paper were obtained from OpenNeuro Larynx Project, and can be downloaded at the following link: https://openneuro.org/datasets/ds002634/versions/3.0.0

The code used in this paper can be found in the following github: https://github.com/Garmanta/LarynxCong

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