The Necessity of Coil Sensitivity and Gradient Non-Linearity Distortion Corrections in Prospective Motion Correction

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INTRODUCTION: Patient motion during an MRI of the brain can result in non-diagnostic image quality. Even with perfect prospective motion tracking and correction, the varying coil sensitivity and gradient non-linearity can cause significant artifacts that cannot be corrected prospectively. Gradient non-linearity manifests as blurring in addition to spatial distortion (1). In addition, coil sensitivity artifacts are dominant when motion is strong (2). Recently, the correction of both artifacts was demonstrated in simulation and phantom studies (3). In this work, we demonstrate the effect of both residual artifacts in human brain MRI. Moreover, we also show that these effects can be minimized by the proposed iterative reconstruction (3).

METHODS: Experiments were performed on a 7T Siemens scanner equipped with a 24-channel head coil. A volunteer was scanned using 3D MPRAGE at three constant poses. He was asked to move his head after each full scan. The imaging gradients were updated to maintain the imaging volume by prospective motion correction (Mo-Co). The imaging parameters were: TR/TE/TI=2250/2.11/1050 ms, imaging volume =224x224x208 mm^3 (1 mm^3 voxel size). The tracking log file shows up to 3 mm translation and 16 degrees rotation. Corrupted data were created by mixing poses from all three k-space data. The model of the problem can be formulated as follows, if the object moves while the coil is stationary, an MR signal from pose p coil γ will relate to the images as [1] (4).

$$\boldsymbol{m}_{\gamma,p} = \boldsymbol{G}\square\boldsymbol{F}\boldsymbol{W}_p\left(\Omega_{inv}^{p} c_p^{\gamma} \boldsymbol{v}_0\right) - - - [\mathbf{1}] \text{ ==> Prospective Mo – Co ==> } \boldsymbol{m}_{\gamma,p} = \boldsymbol{F}\boldsymbol{W}_p\left(\Omega_{inv}^{p} c_p^{\gamma} \boldsymbol{v}_0\right) - - - [\mathbf{2}]$$

where $\boldsymbol{G}$: inverse gridding, $\boldsymbol{F}$: discrete Fourier transformation, $\boldsymbol{c}_p^{\gamma}$: sensitivity map of coil γ pose p, $\boldsymbol{v}_0$: unperturbed image, $\boldsymbol{W}_p$: gradient warp operator. Motion of the object is described by a matrix Ω and Ω_{inv}^{p} is its inverse transformation, while $\square$ is the corresponding transformation rule to Ω in k-space. By applying prospective Mo-Co for Cartesian sampling, k-space data are already aligned consistently during data acquisition. As a result, the gridding step is no longer needed [2]. We refer to the two processes of corrections involving $\Omega_{inv}^{p}\boldsymbol{c}_p^{\gamma}$ and $\boldsymbol{W}_p$ as *sensitivity map* and *gradient nonlinearity distortion corrections*, respectively. Sensitivity maps were calculated as a division of individual-channel images by their Sum of Square (SoS) image and further smoothed using a median filter. The gradient displacement fields (warping function) were approximated using a spherical harmonics expansion (SPH) up to 9^{th} order. The conventional 3D warp (4) is applied to each motion pose individually. The new pixel values at warped and/or unwarped spaces were resampled by using a 3D cubic interpolation. The large linear problem [2] was solved by using Augmented Cartesian SENSE (3).

RESULTS: Fig.1a shows blurring and intensity non-uniformity artifacts in the SoS image and also on the lateral sagittal image in Fig.1d that was cut along the white line of Fig.1a. If geometric distortion correction was skipped from Augmented Cartesian SENSE, a small blurring artifact appears as shown in Fig.1b and 1e. Both artifacts mentioned above were reduced remarkably after applying Augmented Cartesian SENSE with gradient induced distortion correction as shown in Fig.1c and 1f. The zoomed images #1 and #2 are from the yellow dash boxes of Fig.1b and 1c, respectively. Small structural differences appear because of through-plane distortion.

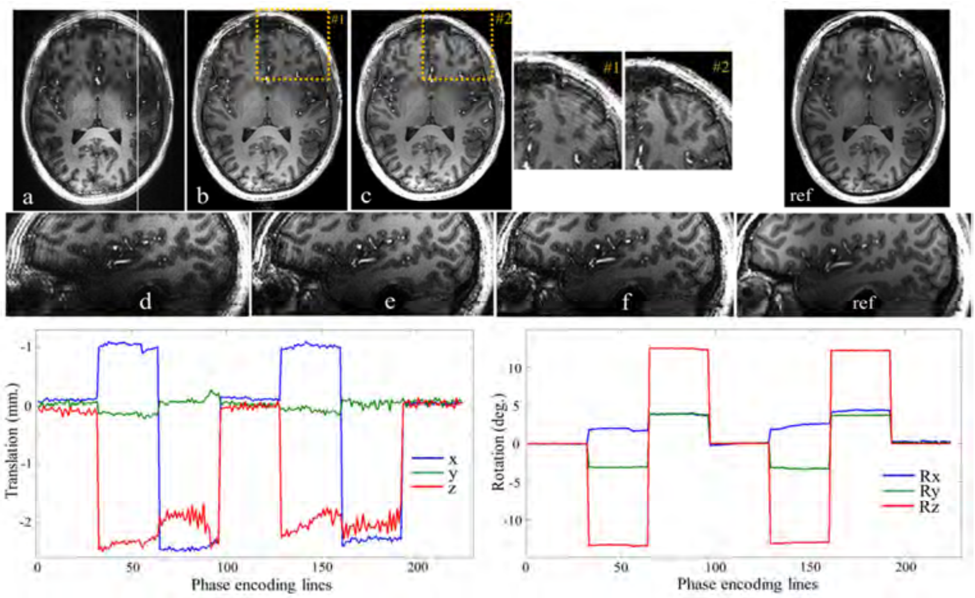

FIG. 1: The images that were reconstructed by SoS, Augmented Cartesian SENSE without, and with geometric distortion correction are a and d, b and e, c and f, respectively. The reference images (ref) are SoS images (pose1 dataset) with gradient warp correction. The last row demonstrates the head motion patterns.

DISCUSSIONS: We demonstrate that head motion can cause residual artifacts after applying prospective Mo-Co. Gradient nonlinearity causes distortion in all three dimensions (5) particularly at remote region that are further away from the isocenter of the scanner. Thus, 3D data may be better to correct than 2D. In addition, the warping function expanded by SPH appears to be an appropriate approximation to correct geometry. In this study, prospective Mo-Co (6) worked highly accurate because residual rigid body errors cannot be recognized after the correction of coil sensitivity mismatch and gradient induced distortion (Fig.1c and 1f.) when visually compared to the reference images (ref). We conclude that the coil sensitivity and gradient distortion artifacts have to be considered for strong motion even after applying adequate prospective Mo-Co.

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