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Motion corrected MP2RAGE neonatal imaging at ultra-high field with inline reconstruction.

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Synopsis

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Motivation: Traditionally acquired 3D MP2RAGE datasets are liable to motion artefacts due to long scan times. This is exacerbated in neonatal scanning when motion is involuntary and unpredictable.

Goal(s): Combine an optimized MP2RAGE 7T neonatal protocol with DISORDER joint motion estimation and image reconstruction and implement Gadgetron inline reconstruction.

Approach: A neonatal cohort was scanned at 7T using our motion corrected MP2RAGE acquisition. Reconstructions were processed offline or inline before qualitative and quantitative assessment of image quality.

Results: Images after motion correction are sharper and show reduction in image artefacts across all 18 datasets. Quantitative metrics and radiologist scores are improved with statistical significance.

Impact: DISORDER acquisition and reconstruction significantly improves the quality of T1w neonatal imaging at 7T using MP2RAGE, as indicated by both quantitative metrics and radiological scoring. Deployment of Gadgetron-based inline DISORDER reconstruction enables scanner preview of the motion corrected 3D volumes.

Introduction

Magnetization Prepared 2 Rapid Acquisition Gradient Echoes (MP2RAGE) sequences[1] are often used at 7T to achieve 3D T1-weighted structural imaging of the brain. Two rapid gradient echo readouts are acquired after an inversion pulse to yield INV1 and INV2 images that are combined to produce a uniform (UNI) image with maximum contrast between white matter, gray matter and cerebrospinal fluid. β enables background suppression for UNI image display[2]:

$$S_{UNI} = \frac{Re(S^*_{INV1}S_{INV2}) - \beta}{|S_{INV1}|^2 + |S_{INV2}|^2 + 2\beta}$$

Scan times for 3D MP2RAGE brain volumes generally exceed several minutes, so motion correction is necessary to avoid imaging artefacts; this is especially important in neonates who often move their heads during acquisitions even when asleep. Previously, we optimized MP2RAGE for contrast-to-noise ratio at 7T and demonstrated high-quality healthy children/adult volunteer[3] and neonatal imaging[4]. Though from prior experience, 54.5% (6/11) of Cartesian-sampled neonatal acquisitions were impacted by motion, even when acquisition order was adjusted to select times when subjects were likely to be most still.

DISORDER is a retrospective motion correction framework that leverages a dedicated self-navigated trajectory to jointly estimate the motion history and image from one acquisition[5]. To address the issue of motion in neonatal 7T MP2RAGE acquisitions, we combined our optimized MP2RAGE protocol with DISORDER and implemented this reconstruction inline via Gadgetron[6].

Methods

18 infants were scanned (8 female, postmenstrual age at scan 39±3 weeks) following written parental consent (NHS REC: 19/LO/1384). A MAGNETOM Terra 7T system (Siemens Healthineers, Forchheim, Germany) was used with a 1Tx/32Rx head coil (Nova Medical) and a locally-modified safety model[7]. Scanning was completed during natural sleep. MP2RAGE scan parameters were TR=5s, TE=2.87ms, TI_1=1.27s, TI_2=2.77s, FA_1=4°, FA_2=3°, GRAPPA factor=3 and slice partial Fourier=6/8[4]. 0.8mm isotropic resolution was achieved with whole-brain coverage in a scan time of 6mins29s. Of 18 subjects scanned, 15 datasets were reconstructed offline and the most recent three (#13-15) were reconstructed using Gadgetron[6] inline reconstruction (Intel(R) Core(TM) i9-10920X CPU, 125GB RAM+64GB swap; 2 GeForce RTX 2080Ti GPUs) with images returned to the scanner alongside conventional reconstructions for comparison.

Reconstructed UNI image quality was quantified using normalized gradient squared[8] (NGS) for assessment of blurring caused by motion, after masking to remove background noise. UNI images were blindly scored by a radiologist according to diagnostic quality and image quality within 19 brain regions on a 1-5 scale (1=poor, 2=fair, 3=good, 4=very good, 5=excellent). Two-tailed paired t-tests assessed differences between uncorrected and motion corrected reconstructions (Figures 3A-E) and a two-way ANOVA with Tukey multiple comparisons assessed individual brain region differences (Figure 3G).

Results

Figure 1 displays central slices for INV1 and INV2 images, and background suppressed UNI images from one subject. Motion correction provides image sharpness improvements and artefact reduction. Corresponding rigid motion traces estimated by DISORDER show the infant moved most significantly towards the end of the acquisition.

UNI image quality improves after motion correction for all subjects (Figure 2). Obvious motion artefacts appear in 44.4% (8/18) of uncorrected cases but only 5.6% (1/18) after correction. The most substantial motion was estimated for Subject 10 (~43mm translation/~35° rotation); although due to the extent of this motion, complete correction was unachievable. Radiologist scores are unchanged for this case but the corresponding report highlights some diagnostic information after correction only. The least motion was observed for Subject 5 (~0.5mm translation/~0.5° rotation) with UNI images before and after correction appearing and reporting similarly.

Quantitative metrics (Figure 3) show consistent improvement; NGS is higher ($p<0.0001$) after motion correction. The ratio of corrected to uncorrected NGS in Figure 3B is >1, indicating improvement for all cases. Radiologist scores corroborated this, as diagnostic and average image quality metrics significantly improved for all cases after motion correction ($p<0.0001$). Improvements were statistically significant ($p<0.001$) for all brain regions except the orbits and globes ($p=0.173$).

Gadgetron reconstruction was successfully implemented with reconstruction times of ~15mins per dataset. Corrected INV1, INV2 (magnitude and phase) and UNI images were returned to the scanner (Figure 4) for radiographer review, as well as uncorrected UNI images for comparison.

Discussion and Conclusions

We show that DISORDER motion correction significantly improves image quality of neonatal MP2RAGE datasets at 7T via

Figures

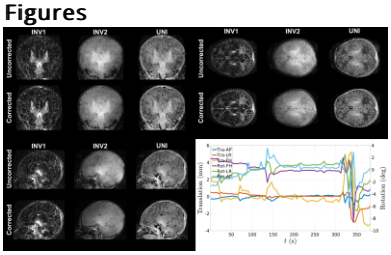


Figure 1: INV1, INV2 and UNI images (with background suppression) in three orientations for a single subject (#9) without motion correction (uncorrected) and after reconstruction using the DISORDER pipeline (corrected). Corresponding motion traces for INV1 are shown on the bottom right-hand side as an example.

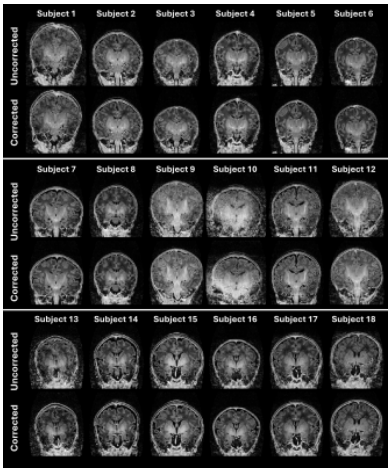
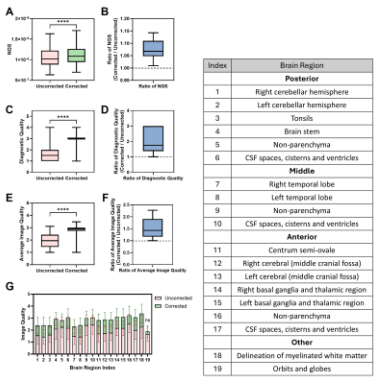


Figure 2: Background suppressed UNI images before and after correction for all subjects for a single coronal slice. The inline Gadgetron reconstruction pipeline was applied for Subjects 13-15. Subtle motion is corrected for and artefacts from extreme motion are reduced.



Index	Brain Region
	Posterior
1	Right cerebellar hemisphere
2	Left cerebellar hemisphere
3	Tonsils
4	Brain stem
5	Non-parenchyma
6	CSF spaces, cisterns and ventricles
	Middle
7	Right temporal lobe
8	Left temporal lobe
9	Non-parenchyma
10	CSF spaces, cisterns and ventricles
	Anterior
11	Centrum semi-ovale
12	Right cerebral (middle cranial fossa)
13	Left cerebral (middle cranial fossa)
14	Right basal ganglia and thalamic region
15	Left basal ganglia and thalamic region
16	Non-parenchyma
17	CSF spaces, cisterns and ventricles
	Other
18	Delineation of myelinated white matter
19	Orbits and globes

Figure 3: (A) UNI image quality based on NGS calculated in brain masks of uncorrected and corrected images. The ratio is plotted in (B); a value >1 indicates improvement after correction. (C-G) show results from blind radiological scoring: (C) and (D) show diagnostic quality scores and ratio respectively; (E) and (F) show brain-region-averaged image quality scores and ratio respectively; and (G) shows image quality scores for all brain regions separately (numbered according to the table on the right-hand side).

quantitative analysis and radiological scoring. The latter also included a comparative assessment in which the corrected result was consistently favored due to superior image sharpness.

Further improvements are possible by trading-off total reconstruction iterations with reconstruction duration. Images become available on the scanner after ~15mins, allowing radiographers to view results while other acquisitions are running but not if the scan is run towards the end of the protocol. Pose-dependent B0 correction[9,10] has shown potential for additional image quality improvements in mild motion cases.

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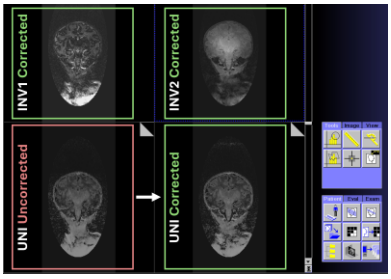

Figure 4: Screenshot of the viewing tab on the MAGNETOM Terra 7T system showing DISORDER reconstruction results for a single subject (#13): magnitude of INV1 after motion correction, magnitude of INV2 after motion correction, and the resultant UNI image after motion correction (all highlighted in green). The UNI result before motion correction (highlighted in red) is also sent back to the scanner for comparison. UNI motion artefacts are visibly reduced.