Improving Rigid Head Motion Correction Using Parallel Imaging

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Introduction. Involuntary patient motion is still a great challenge in MRI. Specifically, in the elderly and pediatric patient population or in patients whose medical conditions (tremor, seizure, stroke) preclude them to hold still, effective strategies to compensate for motion are paramount. In this study, a variant of parallel imaging is introduced that can correct *k*-space inconsistencies arising from rigid body motion (rotation or translation). This motion correction scheme first identifies the degree of motion, corrects the *k*-space data accordingly and thereafter employs an augmented conjugate gradient based iterative image reconstruction to synthesize missing data in *k*-space. The method is described and verified in simulated interleaved EPI and spiral images scans as well as *in vivo* using bi-density spiral scanning.

Materials and Methods: *Reconstruction* – Generally, an object rotation in image space is paralleled by a similar rotation of *k*-space data, whereas translations are reflected by linear phase rolls. If these motion components are known, *k*-space data can be corrected for but usually leading to a fragmentation of *k*-space (Fig 1). This, in turn, gives rise to significant ghost artifacts in the final image. Our correction builds upon an augmented version of an iterative SENSE reconstruction[1] and is performed as follows: 1) counter-rotating *k*-space data by applying the corresponding rotation matrix to the *k*-space trajectory coordinate points of each profile/interleave prior to gridding. 2) Rotating the coil sensitivity map that enters the encoding matrix $\mathbf{E}^1$ for each profile/interleave. This rotation is necessary because even if the object is rotated back to its desired position, different regions of the object have been exposed to different coil sensitivities during the acquisition. 3) Correcting the altered sampling density after rotation. In this study, Voronoi tessellation has been used to derive the new sampling density from the rotated *k*-space trajectories (Fig 1). 4) Phasing the data to account for translation by applying the correction term $p_{corr}(\kappa) = \exp\{-j(2\pi\delta x/FOV_x)\,(k_x(\kappa)/[k_{x,max}-k_{x,min}]) - j(2\pi\delta y/FOV_y)(k_y(\kappa)/[k_{y,max}-k_{y,min}])\}$ to the original *k*-space data prior to gridding.

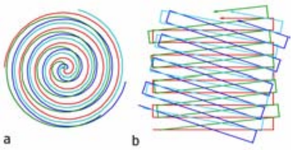

***Fig. 1** – Interleaved spiral (a) and EPI (b) after correction of rotational motion are left with undersampled areas in k-space.*

Motion detection – Various methods exist to derive the extent of translational and rotational motion from MR data. In this study, the motion information was extracted from navigator echoes. The navigator information can be derived from the scan trajectory itself (i.e. self-navigating trajectories) or alternatively from a separate acquisition that provides a low resolution image. Here, a multi-grid registration approach was used that finds the maximum Pearson correlation between a reference image and individual navigator images and provided a reliable estimate of the amount of rotation and translation relative to the reference image (average over all images). To increase robustness and to improve the accuracy of co-registration this step was repeated at least twice.

Experiments – Synthetic data for interleaved spiral and EPI acquisitions (8 interleaves) were generated by using inverse gridding operations[2] on a motion corrupted phantom. For each of the eight interleaves a random head rotation (range ±30°) and translation (range ±15mm) was generated. Prior to the inverse gridding step, each of the individually rotated and shifted images were multiplied by coil sensitivities simulating receiver coil sensitivities from six coils that were attached around the circumference of the object. *In vivo* validation was performed in 3 healthy volunteers using T2w spin echo scans with an interleaved spiral-in/spiral-out readout and an 8-channel head coil. The spiral-in part (3-5ms duration) provided for each interleaf data a low resolution navigator image (32^2). The spiral-out part was a normal interleaved spiral acquisition: TR/TE=4,000ms/85ms, slice thickness/ gap=4/1mm, 17 slices, FOV=24cm, matrix=256, interleaves = 32, and NEX=1. The receiver bandwidth for the spiral acquisition was +/- 125kHz. During each experiment the volunteers were asked to rotate and/or shift their heads at three increasing levels of motion (no, mild [~±15°], and moderate [~±25°] motion).

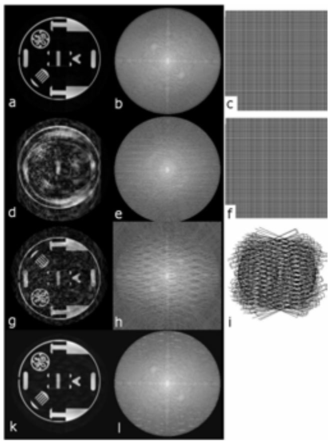

***Fig. 2** – a) Gridding reconstruction of a phantom without rotation, b) gridded k-space data, and c) EPI sampling trajectory. d) Gridding reconstruction of rotation corrupted data, e) corrupted k-space, and f) trajectory used for gridding. g) Gridding reconstruction of rotation corrupted data but with rotation corrected sampling trajectory, h) gridded k-space with variable sampling density and regional undersampling, and i) rotation corrected trajectory used for gridding. k) Resulting image after correction for altered coil sensitivity and iterative SENSE reconstruction (10 iterations) and l) corresponding k-space.*

Results: Significant motion artifacts are apparent in our simulated data when acquired *k*-space data are gridded without considering the object motion (Fig 2). The situation can be slightly ameliorated if the *k*-space data are properly phased and rotated to account for translational and rotational motion within each interleave. However, significant patches of local undersampling will remain in *k*-space after this correction giving rise to noticeable aliasing artifact. The newly proposed algorithm efficiently removes a large portion of these gaps by taking advantage of parallel imaging. In the final image (Fig 2k) the motion artifacts could be dramatically reduced. The data in Fig 3 were acquired with a new spin echo spiral-in/spiral-out sequence. The low-resolution image of the spiral-in part allows one to detect motion between interleaves and serves also as a coil sensitivity calibration scan for each interleaf. As expected, there was no difference in the reconstructed images with and without motion correction in the absence of motion. However, substantial improvement in image quality was observed when the correction was applied to motion corrupted data. Of course, with increasing motion the correction efficacy diminishes. This is due to some extent to excessive gaps in *k*-space and increasing contributions of through-plane motion. However, except for the severe cases of motion, the image quality after correction improved considerably.

Conclusion. A variant of parallel imaging has been introduced that can correct *k*-space inconsistencies arising from rigid body motion. It was combined with an image-registration based method to detect these motion patterns using navigator images. The reconstruction part works for arbitrary *k*-space acquisition patterns as long as sufficient coil sensitivity information and reliable motion information is provided. The latter can be provided either by external head tracking methods or more easily via navigator images. The method is limited to in-plane motion only and does not correct for spin history effects. This is however a shortcoming of all retrospective motion correction schemes and not a limitation of the method proposed herein. With small modifications to existing iterative SENSE reconstruction algorithms[1] an effective motion correction scheme can be incorporated into sequences that provide navigator information. The method was simulated for spirals and EPI and tested in spiral-in/spiral-out acquisitions only but certainly can be combined with other trajectories or conventional parallel imaging methods.

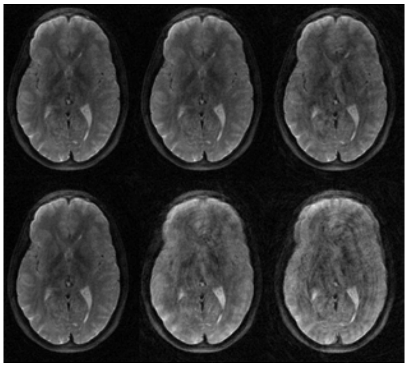

***Fig. 3** – (top row): Motion corrected T2w spiral scans. Left to right: no, mild, and moderate motion. (bottom row): Images without motion correction. Left to right: no (reference image), mild, and moderate motion. Without correction (bottom row) mild motion causes significant artifacts that are mostly apparent in the frontal brain. Increased image distortions can be seen for moderate motion. Significant artifact reduction can be achieved with the parallel imaging based correction scheme. With moderate motion some residual artifacts are apparent due to the severity of motion. Without motion the algorithm does not alter the image quality (left column).*

References: [1]Pruessmann K, *et al.* MRM 46: 638-51, 2001; [2]Rasche V, et al. IEEE TMI 18: 385-92, 1999.

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