Motion insensitive 3D imaging using a novel real-time image-based 3D PROspective MOtion correction method (3D PROMO)

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Introduction

Patient motion during an MRI scan can cause significant artifacts in the acquired images, compromising their diagnostic value. This is especially problematic in certain "uncooperative" patient populations (e.g. children, the elderly, those suffering from movement disorders) and during long high-resolution 3D scans. Although retrospective un-navigated motion correction methods such as [1] have been proposed, prospective navigated techniques [2, 3], which estimate and correct all 6 rigid body motion parameters (termed "3D" motion correction), provide a more direct and complete measure of motion and it's concomitant effects (like changes in spin history and shim). However, these prospective motion correction methods require strict adherence to the rigid body assumption – limiting the accuracy of estimates, even in the head, where regions like the neck, jaw, and orbits move non-rigidly with respect to the brain. Here we propose a novel image-based *3D PRO*spective *MO*tion correction method (*3D PROMO*) that minimizes the adverse effects of non-rigid motion. To demonstrate its feasibility, 3D PROMO was implemented and used for real-time motion correction during *in vivo* high-resolution 3D T1-weighted scans of the brain.

Methods

Image Acquisition: Navigator pulses and code for real-time slice/slab re-positioning were integrated into a 3D inversion recovery spoiled gradient echo pulse sequence (IR-SPGR). Centric kz ordering was used, with an entire kx-kz plane acquired after every inversion pulse. The thickness of the IR pulse was twice that of the imaging slab. Pulse sequence parameters: TE/TR=3.9/8.7 ms, TI=700 ms, FA=8^o, BW=±15.63 kHz, FOV=24 cm, acquisition matrix=192x192x170, voxel size=1.2x1.2x1.2mm.

Spiral Navigators: Three orthogonal low-flip, thick-slice single-shot spiral acquisitions (S-Nav) were inserted in the 3D IR-SPGR sequence prior to each inversion pulse (Fig 1a). Images reconstructed from these spiral acquisitions were used as inputs into the motion estimation algorithm. The total time for the S-Nav acquisition (all 3 orthogonal planes) was ~40ms. Low flip angles were used to minimize saturation effects that could otherwise adversely impact the imaging volume. S-Nav parameters: TE/TR=3.4/14 ms, FA=5^o, 2048 points, FOV=300 mm, slice thickness=19mm, BW=±125kHz.

Motion Estimation and Correction: The current implementation of 3D PROMO relies on a well-known and widely-used non-linear filter, the Extended Kalman Filter (EKF) [4], for estimation of all 6 rigid-body motion parameters (x, y, and z translations and rotations about x, y, and z). S-Nav images and the previously applied motion parameters are passed to the EKF algorithm following each S-Nav acquisition (Fig 1b). S-Nav images are masked to exclude areas that move non-rigidly with respect to the brain (e.g. neck, jaw, orbits). These masked images are then used to calculate new motion estimates. Imaging slab and S-Nav slices are repositioned based on these estimates before acquisition of the next kx-kz plane (Fig 1c). In cases where the EKF algorithm estimates large amounts of motion, the corresponding kx-kz planes are re-scanned – providing an efficient "knowledge-based" means of k-space "oversampling."

Real-Time Framework: A socket-based communication framework, developed on a GE 1.5T Signa HD system (Waukesha, WI), enables efficient and near real-time communication of navigator data, associated meta data, and estimated motion parameters between the motion estimation algorithm and the scanner pulse sequence/receive chain.

In vivo Experiments: Using the imaging parameters stated above, volunteer experiments were performed - following informed consent - to explore the feasibility of 3D PROMO for accurate estimation and correction of motion during *in-vivo* 3D high resolution imaging. The experiments consisted of 3 scans (a) a baseline "gold-standard" scan where the volunteer was asked to stay as still as possible, (b) a scan without motion correction where the volunteer was asked to perform a single sudden motion during the scan, and (c) a 3D PROMO scan where the volunteer approximates the same sudden motion as in (b).

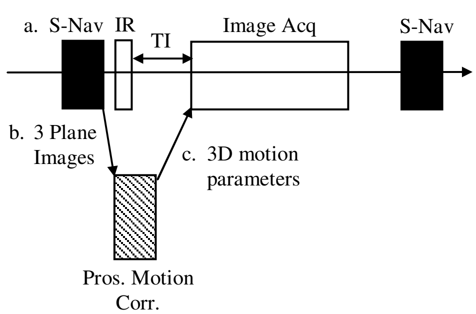

Figure 1: Block diagram of the modified pulse sequence. New motion parameters are estimated prior to acquisition of each kx-kz plane.

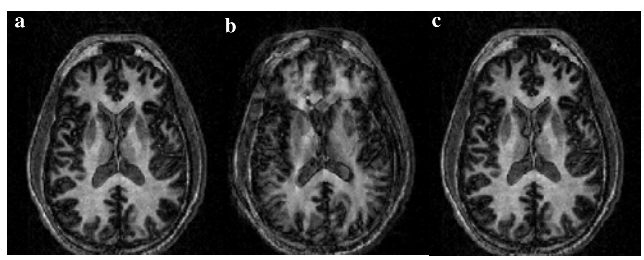

Figure 2: Images from volunteer experiments. The same slice is shown in all the three cases. (a) No motion (b) Motion with no correction (c) Motion with correction (3D PROMO). There was significant improvement in image quality with 3D PROMO, (b) vs (c). Image quality was qualitatively similar between (a) and (c).

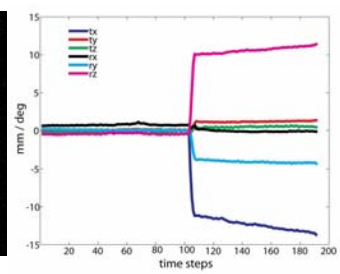

Figure 3: The diagram shows the 6 rigid body motion estimates (mm or degrees) during a volunteer scan.

Results

As shown by representative images in Fig 2, 3D PROMO greatly improves image quality (IQ) in the presence of motion. The IQ obtained during motion (Fig 2c) was qualitatively comparable with the IQ acquired during no motion (Fig 2a). In the case shown in Fig 2c, 5 kx-kz planes were re-scanned, yielding a moderate 3%, increase in scan time. As also shown in Fig 2, inserted S-Nav pulses did not cause noticeable saturation effects in images acquired with 3D PROMO. Figure 3 shows all 6 rigid-body motion estimates calculated in real-time during the high resolution 3D scan. Note the stability of the estimates during the long periods of minimal motion prior to, and after, the volunteer's sudden movement.

Discussion and Conclusion

This study demonstrates the feasibility of a novel image-based 3D prospective motion correction technique (3D PROMO) to accurately estimate all 6 rigid body motion parameters in real-time. Once calculated, these estimates are immediately used to correct slab/slice position and orientation, resulting in artifact-free 3D images. Although the S-Nav acquisition is moderately long, it still provides a time-efficient means to acquire image-based navigators for magnetization-prepared 3D SPGR sequences (e.g. IR-SPGR) and sequences which contain inherent dead time (e.g. 3D FSE). Future 3D PROMO work may investigate the feasibility of applying the image-based 3D PROMO approach to motion insensitive imaging in other anatomical regions where non-rigid motion is more prevalent (abdomen, spine, etc).

Acknowledgements

The authors would like to acknowledge Maggie Fung and Jeff Stainsby for helpful discussions. The authors would also like to thank Rebecca Theilmann, David Ferguson and Cathy Leonard for their invaluable assistance.

References [1] McGee et al, AJR 2001. [2] Ward et al MRM 2000. [3] van der Kouwe et al, MRM 2006. [4] Anderson et al, Optimal Filtering 1979.