New Strategy for Simultaneous Suppression of Intra- and Inter-Slice Motion

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Synopsis
We introduce a new method to simultaneously address the problems of intra- and inter-slice in-plane motion estimation. The new method works for sequences in which the k-space is collected as small number of bands. Instead of repeating the acquisition in the same format for the extra acquisitions when NEX>1, we present a new strategy to achieve the same NEX via overlapped acquisition. The overlapping area between consecutive acquisitions is used to estimate both translation and rotation parameters, which are subsequently used to perform correct reconstruction.

Introduction
Motion artifacts can generally be classified into either intra-slice or inter-slice motion. The first is the result of motion in between the acquisition of different portions of the k-space while the second is the result of motion in between acquisitions of the same slice. The techniques in the literature often treated these types in completely different manners with several strategies to suppress each type independently. Given their underlying similarities, it might be advantageous to treat both problems simultaneously. In this work, we propose a new approach for suppressing motion artifacts from both types. The proposed method assumes rigid body motion and corrects for both its translational and rotational motion components without need for extra acquisitions.

Methods
Starting from the general assumption of rigid body motion, we consider the case when the acquisition of the k-space is in the form of bands of finite number of lines arranged in a rectilinear fashion to cover the k-space area of interest. We also assume that an averaging factor of at least two is desired (i.e., NEX ≥ 2 to make the inter-slice motion problem nontrivial). Instead of acquiring a full k-space of each image and then averaging the result, we propose a new acquisition strategy based on acquiring the k-space in consecutive bands having (100·(NEX-1)/NEX)% overlap going from one end of the phase encoding direction to the other end. For example, when NEX is 2, the overlap will be 50%. In case of no motion, this overlap provides the additional acquisitions required by the selected NEX value. On the other hand, when motion occurs, the rotation of an object in the image domain results in the same rotation of its k-space, while translational shift results in a linear phase term multiplied in the k-space. In such case, the proposed overlap provides valuable information that enables the determination of motion parameters as a generalization of the floating navigator echo (1). The process of estimating the motion parameters is done in two steps: rotation estimation then 2-D translation estimation. From the geometry of the acquisition in the k-space, the presence of rotation amounts to varying the area of overlap between the two consecutive bands or blades. Hence, given that this geometry is known *a priori*, if we compute a similarity measure between the areas of overlap at each possible rotation angle within a predetermined range of possible angles, it is possible to determine the rotation angle as the one having the highest similarity measure. We tried two different methods to do that. The first is based on a correlation coefficient between the elements in the overlapped areas to allow for the similarity measure to be independent of the size of the overlapping area. On the other hand, the second is based on matching the intensity on an arc within the overlapped area that is centered at the center of the k-space (as shown in Fig. 1). The estimation of rotation in this method is performed is similar to orbital navigator (2) performed on an arc instead of a circle. This approach is therefore termed arc navigator (aNAV). Points on this arc are interpolated to any desired resolution from the two acquired overlapping bands using bilinear interpolation to form aNAV data vectors. Rotation of the k-space results in identical rotation of this arc, which appears as shift in the aNAV signals and can be determined by simple correlation or in the frequency domain by fitting the phase difference between the Fourier transforms of the two aNAV signals. Once the rotation is determined, it is straight forward to determine the 2-D translation by fitting the phase difference between the points in the overlapped areas to a linear function in k_x and k_y. The phase difference is computed for each point as the phase of the complex multiplication of that point in the second band and the conjugate of the one in the first to avoid phase wrapping errors. This process is repeated between each two consecutive bands with correction for translational motion for the most recently acquired band. On the other hand, the rotational motion can be corrected only during the reconstruction process given the sampling non-uniformity introduced into the k-space by this type of motion. In its simplest form, the reconstruction has to include an interpolation step to calculate the k-space data on a rectilinear grid. More elaborate techniques can also be used for more accurate reconstruction such as algebraic reconstruction (3) and conventional gridding (4).

Results and Discussion
The proposed algorithm was verified using simulated motion on numerical phantoms as well as images of an induced motion of a phantom obtained on a Siemens 1.5T system. The acquisition parameters were as follows: fast spin echo, TR 500ms, TE 15ms, Matrix 256x256, and ETL: 16. Fig. 2 shows a sample plot of the aNAV signals from two bands with a relative rotation of two degrees. The apparent similarity between the curves allows for accurate estimation of the rotation angle. A wide range of motion was simulated to test the accuracy of the proposed method and simulation of noisy data was performed to test the robustness of the solution under different SNR conditions. The results indicate that the new method is capable of detecting rotations with a mean error as low as 0.1 degrees and translation with an error that is always less than 0.1 of the pixel width. Given that the similarity measures used implicitly average the data, the technique was found to be robust against noise in most cases.
It should be noted that the arc angle of aNAV, and hence the maximum rotation captured, depends on the distance of the acquired band from the k-space origin. The closer the band from the origin, the wider its viewing angle becomes. The far most band has an arc angle of $\pm \cos^{-1}(1-M/(N-M))$ where N is the number of phase encoding lines and M is the number of lines per band. For a typical image resolution of 128 and band size of 16, one can obtain an arc angle of at least ± 31°. This allows the robust detection of a relative rotation between two consecutive bands of more than ± 15° under the worst-case scenario. In cases when the SNR is too low, the strategy based on correlation coefficient is preferred in spite of its extra computational effort.

Conclusions
A new acquisition and processing strategy was proposed to suppress both intra-slice and inter-slice motion types. The new method was implemented and verified using simulated motion on numerical phantom as well as real images and the results support the proposed hypothesis. The new technique has the advantage of not requiring additional acquisition as well as being not demanding as far as its required computational effort.
*This work was supported in part by NIH (grants RO1MH55346 and RO1EB00321), Georgia Research Alliance, and The Whitaker Foundation.

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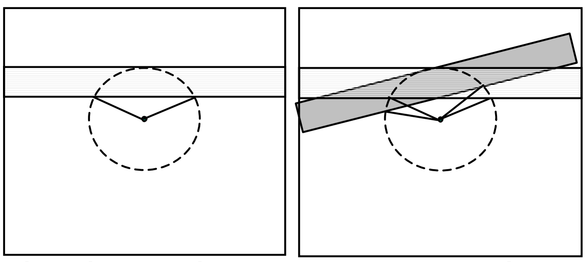

Fig. 1: The overlapping area between consecutive acquisition with no motion (left) and with rotation (right) showing the aNAV position in each case.

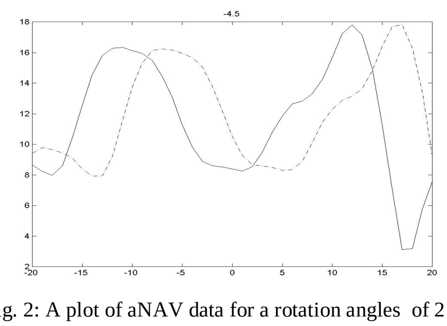

Fig. 2: A plot of aNAV data for a rotation angles of 2 degrees showing a shift corresponding to exactly this angle.