Floating Navigator Echo for In-Plane Translational Motion Estimation

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Abstract
We propose a new technique in which the navigator echo is taken at an arbitrary location in k-space. The new technique acquires the same line in k-space in each two consecutive sets of lines. Unlike the classical formulation, we show that the translational motion in both the read-out and phase encoding directions can be computed from this repeated line. This also allows the implementation of navigator echo to be simpler and echo time to be shorter since the k-space line location for the navigator echo adheres to the acquired portion of k-space.

Introduction
Motion of patient during MR acquisition causes severe artifacts in the reconstructed images. Among the most successful techniques used to suppress such artifacts is the navigator echo technique (1). The original formulation relies on acquiring an extra line in the center of k-space along the k_x or k_y directions to detect motion in that direction. This requires an extra amount of time to acquire this line prior to actual k-space acquisition with each RF pulse and hence limits the minimum TE of such sequence in addition to additional complexity in sequence programming. Also, the detection of motion in both the read-out and phase encoding directions is not possible with a single line. In this work, we introduce a modified version of the navigator echo technique that alleviates these problems. In particular, the acquisition of the navigator echo data is done close to the acquired k-space region and allows the simultaneous estimation of detecting translational motion in both directions.

Methods
For fast imaging techniques such as fast spin echo, instead of acquiring the navigator echo line in the center of the k-space, we acquire this line by acquiring k-space sections that overlap in a single line (see Figure 1). This line of overlap, termed the *floating navigator echo (fNAV)* to indicate that it does not have to be central, is used as the navigator echo between two consecutive k-space segments acquisitions. From the Fourier transform shift theorem and the central slice theorem (2), the inverse Fourier transform of fNAV corresponds to the projection of a modulated version of the 2-D object within the slice. The modulation frequency is a direct function of the distance of the fNAV line from the center of the k-space. Two things should be observed in this case. First, this modulation is the same between the two consecutive fNAV lines because of overlapping. Second, the effect translational motion in the read-out direction on the projection is independent from such modulation. Hence, the motion in the read-out direction can be obtained in the same way as regular navigator echo techniques using cross-correlation maximization. On the other hand, by comparing the phase values between two overlapping fNAV lines, we can directly estimate the possible values of translational motion in the phase encoding direction as well. In particular, the motion in the phase encoding direction superimposes a linear phase along this direction in the acquired k-space. This additional phase appears clearly in the center point of fNAV where the phase effect from the read-out motion is zero. Hence, by comparing this point between two fNAV lines, we can estimate the phase difference, and hence the motion, between the two acquisitions. Given the possibility of phase wrapping in cases of severe motion or when the fNAV line is far away from the center of the k-space, possible values of the motion correspond to $(\Delta\phi \pm 2n\pi)/K_y$ for integer value of n. This ambiguity can be solved using focusing measures such as subband registration (3) or entropy (4). Even though such techniques are generally time consuming, the limited set of possible solutions makes their practical use acceptable. It should be noted that fNAV lines must not be at the center of the k-space to be able to estimate the motion in the phase encoding direction.

Results
The proposed technique was implemented to correct simulated as well as experimental data. The simulations used data generated using the exact form of a Shepp-Logan phantom (i.e., sampling the exact Fourier transform expression of the phantom defined in (5)). The motion estimation in both directions had an accuracy of ~0.1 pixels (using appropriate Sinc interpolation in the inverse Fourier transformation step along the read-out direction). The results generally support the theory and indicate the practicality of the new method for clinical use.

Discussion
The method described here is simple to implement and alleviates the problems encountered with the original navigator echo formulation. It enables the estimation of both in-slice translational motion components using a single fNAV. In its present form, it is still limited to estimating only the in-plane translational motion. Generalization of the present form using multiple overlapping fNAV lines could in principle allow the estimation of rotational motion as well.

References
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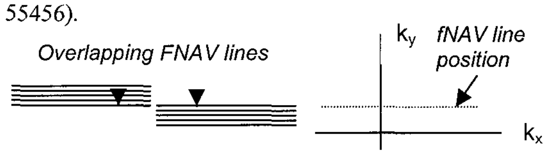

Figure 1. Overlapping fNAV lines and fNAV line position as opposed to the centerline of k-space