The use of Three Navigator Echoes in Cartesian EPI Reconstruction Reduces Nyquist Ghosting

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Introduction: Echo planar imaging (EPI) is predominantly used for fast imaging applications. With Cartesian EPI, k-space is sampled with parallel lines in alternating directions. Slight offsets in the timing between the acquisitions of the alternating lines caused by hardware timing errors and eddy current effects lead to Nyquist ghosting. Multiple methods have been developed to reduce such Nyquist ghosts, some based upon image-space processing [1] and others based upon estimating the k-space offsets ([2],[3],[4]). Image-space processing methods require user interaction to identify image regions of pure artifact, which can become prohibitive in large functional runs with hundreds to thousands of images. Current k-space methods either assume that the offsets are constant over time [2] or require iterative methods [4]. The proposed three navigator echo method described here allows for the unsupervised determination of the timing offset and the center frequency offset for each acquired image without requiring an iterative solution.

Theory: As it has been previously shown [4], the acquired signal for even and odd k-space lines after the necessary reversal of the odd line is: $s_n^{even} = \exp[i\omega_0(n\tau - \Delta)]\exp[i\omega_0 t]f_n(t-\Delta)$ and $s_n^{odd} = \exp[i\omega_0(n\tau + \Delta)]\exp[-i\omega_0 t]f_n(t+\Delta)$. In these equations, ω_0 is the center frequency offset, n is the acquired line number, τ is the effective echo spacing, $f_n(t)$ is the Fourier transform of the projection through the center of the image, and Δ is a function of ω representing the k-space time offset. After Fourier transformation the lines are: $p_n^{even} = \exp[i\omega_0 n\tau]\exp[-i\omega\Delta]F_n(\omega - \omega_0)$ and $p_n^{odd} = \exp[i\omega_0(n\tau + 2\Delta)]\exp[i\omega\Delta]F_n(\omega + \omega_0)$. If three navigator echoes are acquired at the beginning of the readout, as four are standard in the GE EPI-RT pulse sequence, the projection envelopes are the same for each line and n is zero for the first line, one for the second line, and two for the third line. Thus, the center frequency offset can be determined from the first and third navigators: $\omega_0 = (-1/2\delta\omega)\arg[NAV1(\omega)^* NAV3(\omega)]$, where $\delta\omega$ is the step between observations in the Fourier space, *NAV1** is the complex conjugate of the Fourier transform of the first navigator, and *NAV3* is the Fourier transform of the third navigator. The center frequency offset is found by the mean of the calculated ω_0 values weighted by the average magnitude of *NAV1* and *NAV2*. The k-space navigator echoes may then be corrected by multiplication with $\exp[i\omega_0 t]$ for odd navigators or $\exp[-i\omega_0 t]$ for even navigators. Then, the time offset as a function of ω can be found directly: $\Delta(\omega) = (1/2(\omega + \omega_0))[\omega_0\tau + \arg(NAV2^* NAV1)]$, where *NAV2** is the complex conjugate of the Fourier transform of the ω_0 corrected second navigator and *NAV1* is the Fourier transform of the ω_0 corrected first navigator. Even and odd echoes may then be corrected by ω_0 correction, Fourier transformation, Δ correction, and inverse Fourier transformation.

Methods: Data was acquired on a General Electric Signa LX 3T imager. Acquisition parameters included: TE/TR 48.8/1500 ms, FOV/slice thickness 19.0/0.2 cm, receive bandwidth 83.3 kHz, 266 repetitions of ten slices of 96x96 acquisition matrix. Standard reconstruction utilizing the reference scan method was performed on the scanner terminal without Gradwarp or apodization and data was also autolocked for offline reconstruction. Ghosting was quantitatively measured using entropy [5].

Results: Figures 1 through 4 illustrate the efficacy of the three navigator reconstruction method. Each image is scaled to minimum to maximum to zero to one. Figure 1 illustrates the Nyquist ghosting present with no navigator correction. Figure 2 includes ghosting resulting from imperfect correction. Figure 3 includes further reduced ghosting from the three navigator method. The mean entropies from the 2660 images are shown in Figure 4.

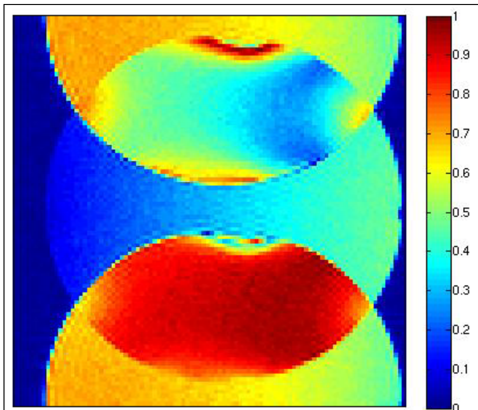

Fig. 1: No Correction

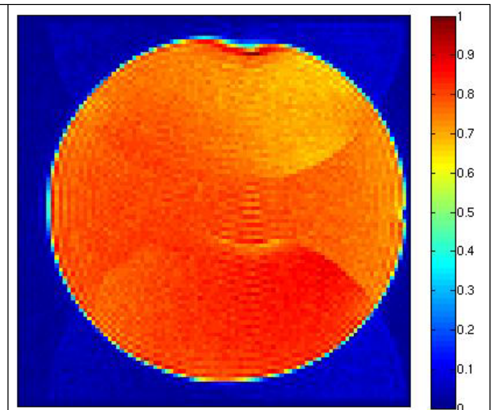

Fig. 2: GE Standard Reconstruction

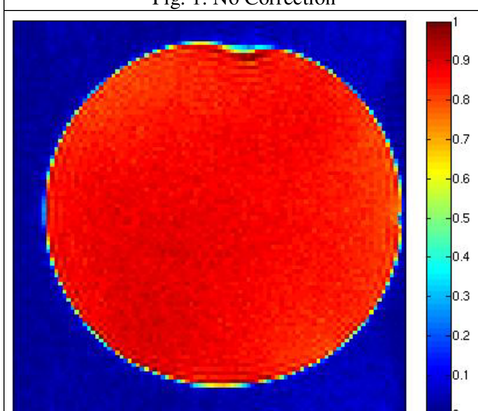

Fig. 3: Three Navigator Reconstruction

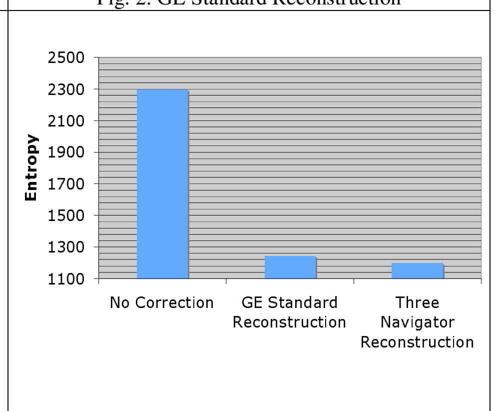

Fig. 4: Mean Entropies from Reconstruction

Discussion: It is apparent that the use of three navigator echoes significantly reduces Nyquist ghost artifacts in Cartesian echo planar images. This method, like the two navigator echo method, does not require a separate reference scan and can estimate the center frequency offset and timing error with each image acquisition. Unlike the two navigator method, the three navigator method is less computationally intensive and does not require iterative techniques.

References: (1) Buonocore, et al. MRM 45: 96-108. (2) Bruder, et al. MRM 23: 311-323. (3) Jesmanowicz, et al. Proc. 12th SMRM: 1239. (4) Jesmanowicz, et al. Proc. 3rd ISMRM: 619. (5) Atkinson, et al. IEEE Trans. Med. Img. 16: 903-910.

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