# Reference Scan Navigator-Aided High Resolution Half *K*-Space Interleaved EPI for fMRI at 3T

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***Abstract***
Interleaved EPI is subject to ghost artifacts. When half *k*-space acquisition is used, the absence of an accurate high-resolution phase map gives rise to additional artifacts. To address these problems, we introduce a phase encoded reference scan technique that also employs navigator echoes. The method can align the even and odd lines in partial *k*-space EPI, generate a good quality high-resolution phase map, and correct for $\omega_0$ shifts. The approach has been evaluated for fMRI at 3T and can be expected to become increasingly useful as the field strength increases.

**Theory and Method**
Equation 1 describes the EPI signal:

$$S(k_x, q\Delta k_y) = \iint M(x', y')\exp\{-i[k_x + (-1)^q \varepsilon]x' - ik_y y'\} \cdot \exp\{-i\lambda(x', y')[a + (-1)^q bk_x + ck_y]\}dx'dy' \quad [1]$$

where $ck_y = cq\Delta k_y$, $c\Delta k_y$ is the time between scan lines, $bk_x = bn\Delta k_x$, $b\Delta k_x$ is the sampling interval, $\lambda(x',y')$ is the spatially dependent magnetic field inhomogeneity, $a$ is the echo time (defined as the time between the center of *k*-space and the center of the excitation RF pulse), and $\varepsilon$ is the time inconsistency between forward and backward scan lines. For simplicity, a constant $\varepsilon$ along $k_x$ is assumed, although this is not precisely the case (1,4). An inverse Fourier transform along $k_x$ will result in

$$I(x, q\Delta k_y) = \iint M(x', y')\exp\{-i[(-1)^q \varepsilon x' + \lambda(x', y')a]\} \cdot \exp\{-ik_y[y' + c\lambda(x', y')]\} \cdot \int \exp\{ik_x[x - x' - (-1)^q b\lambda(x', y')]\}dk_x dx'dy' \quad [2]$$

The off resonance $\lambda(x', y')$ is not only related to $k_x$, but also directly related to $k_y$, which can produce additional ghost artifacts and spatially varying image intensity changes. These effects cannot be corrected by non-phase encoded reference scans (1) or by two reference scan lines (2, 3). When half *k*-space acquisition is employed, a phase encoded reference scan can generate an improved phase map, particularly when the susceptibility effects are relatively large. The pulse sequence diagram is shown in Fig. 1. The interval between blips in the reference scan is twice that of the intervals in the image scan segments. In addition, the first blip has half the amplitude of the following blips. Thus, the odd $k_y$ lines are corrected. By using the method discussed in Ref. 4, we are able to derive and average multiple $\omega_0$ values from the data acquired from each image, which permits $\omega_0$ correction for each image. Interleaved half *k*-space EPI provides an opportunity to increase the resolution of the phase map, because in a fixed TE value and two-shot interleaving, twice as many overscan lines are collected. A navigator echo is used for all reference and image acquisitions.

**Results and Discussion**
This sequence has been implemented in a Bruker 3T scanner using an insertable gradient coil and end cap volume RF coil. Image reconstruction was done offline. Zero order and first order motion correction was done in *k*-space with navigator echoes. Figure 2a shows a two-shot 256 × 256 phantom image at $1\text{mm}^3$ resolution using half *k*-space with 16 overscan lines in each segment. Almost no ghost artifacts were observed, and the distortion in phase encoding direction is about 2 times smaller compared with single short half k space EPI. Figure 2b shows a functional brain map at 1.5 cubic mm resolution using a self-paced finger-tapping paradigm. Scan parameters are two shots, half *k*-space, 128 × 128 matrix size, TR 2s, TE 21.6ms. Use of a phase-encoded reference scan for gradient-recalled EPI was introduced by Hu and Le in Ref. 5, where it was implemented for low resolution (64 × 64). Here we have extended this work to include high resolution partial *k*-space acquisition with navigator echoes. Our approach has enabled us to obtain high resolution GR-EPI fMRI data that is reasonably free from motional artifacts and ghosting. Partial *k*-space acquisition offers several benefits in interleaved EPI – increased flexibility in the choice of TE, time available for a navigator echo, narrowed phase-encode point spread function from T2* decay, and greater overall image brightness. Use of a phase reference scan to correct the lines of *k*-space also leads to improved phase maps in half *k*-space image formation. Because of the long data acquisition time in segmented EPI, navigator echoes are necessary, especially for high resolution interleaved EPI. Yacoub et al (6) reported interleaved half k space EPI at 7T using the reference scan technique of Ref.1. The phase encoded reference scan method together with half k space interleaved EPI has not been reported in this context, and appears to be of value at high resolution.

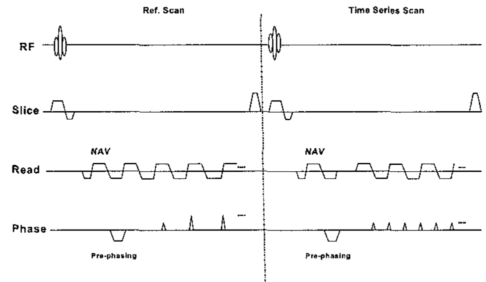


***Fig. 1. Pulse sequence diagram. Reference scans for interleaved segments were employed at the beginning and end of the acquisition of the image time course data.***

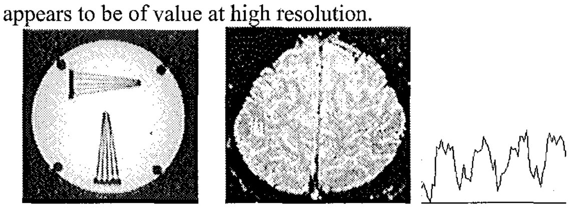

***Fig.2.a*** ***Fig.2.b*** ***Fig.2.c***

***Fig.2a. Resolution phantom at $1mm^3$ resolution 2b. fMRI at the central sulcus at 1.5 $mm^3$resolution. The image was acquired using 2 shot half k space EPI. 2c. Representative time course.***

**References**
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