An Efficient Correction Technique for Constant, Linear and 'Oblique' Phase Errors in EPI-PROPELLER

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Introduction Short-axis and long-axis PROPELLER echo planar imaging (referred to as SAP-EPI and LAP-EPI, respectively) [1, 2] have been developed as alternatives to fast spin echo (FSE)-based PROPELLER sequences [3]. EPI-PROPELLER typically requires fewer shots than FSE-PROPELLER, and is less SAR-intensive. Like other EPI sequences, however, both SAP- and LAP-EPI are sensitive to eddy currents that lead to Nyquist ghosts, therefore requiring phase corrections. Conventional phase-correction techniques rely on reference scans [4]. Since each PROPELLER blade activates a different combination of the physical gradient axes, reference scans on a per-blade basis are typically needed, especially for a gradient system exhibiting non-negligible degree of gradient anisotropy [5-8]. Blade-specific reference scans can considerably increase the total scan time of the otherwise very fast SAP- or LAP-EPI techniques. In this study, we have developed a time-efficient reference scan method to address phase errors in EPI-PROPELLER sequences. In addition to correcting the constant and linear phase errors common to all EPI sequences, our technique is also capable of reducing the phase error along the phase-encoding direction, a phenomenon responsible for the so-called oblique Nyquist ghost (ONG) [6-8] that is particularly relevant to EPI-PROPELLER sequences.

Methods Without losing generality, we demonstrate the proposed technique using a 2D axial scan (in the x-y plane) as an example. The technique acquires only two reference scans along each of the two physical axes, x and y, respectively. The constant (*c*) and linear (*l*) phase errors are calculated from each reference scan and denoted by $c_{||}$ and $l_{||}$ for the x-axis and $c_\perp$ and $l_\perp$ for the y-axis (Figs. 1a and 1b). For any arbitrary blade orientation θ shown in Fig.1, the constant and linear phase errors (c_θ and l_θ, respectively) are calculated using Eqs. (1) and (2) which can be derived with the aid of Figs. 1a and 1b, respectively. With the phase errors now known, phase correction can proceed as if a blade-specific reference scan were acquired. The inconsistent k-space shift along the phase-encoding direction, $\Delta k'_{pe_\theta}$, which originates from gradient anisotropy [5-8] in oblique blades (i.e., $\theta \neq 0°$ or 90°), can be computed and corrected using Eq. (3), which can be derived from Fig. 1c and [7]. Therefore, with the acquisition of only two reference scans, we can synthesize not only the constant and linear phase correction values common to all EPI sequences, but also k-space shifts responsible for ONG in oblique blades.

This technique was implemented on a SAP-EPI sequence developed on a 3.0T GE Signa HDx scanner (GE Healthcare, Waukesha, WI, USA; max. gradient strength = 40 mT/m, max. slew rate = 150 T/m/s). Phase corrections were first evaluated on a square phantom (with 6 cm sides) filled with 100% acetone. The two orthogonal reference scans were acquired first, followed by the acquisition of a SAP-EPI dataset with TR = 3000 ms, TE = 69.6 ms (min. full), bandwidth = ±62.5 kHz, acquisition matrix of 32 readout points × 128 phase-encoding steps, number of blades = 6, NEX = 8, FOV = 18 cm, and slice thickness = 7.5 mm. For comparison, a full set of blade-specific reference scans were also acquired. This protocol was repeated on a healthy male volunteer using similar scan parameters (FOV = 40 cm, slice thickness = 5 mm). Constant and linear phase errors computed from Eqs. (1) and (2) were used to perform phase correction on each blade ('Method A'). In addition, after correcting for the constant and linear phase errors, the ONG correction was also applied based on Eq. (3). For comparison, phase correction was independently performed using the data from blade-specific reference scans ('Method B'). The intensity of the Nyquist ghost before and after each correction was calculated as a ratio of the mean ghost intensity in a region of interest (ROI; ~200 pixels) over the signal intensity of a uniform ROI selected from within the object.

List of Equations

$$c_\theta \propto c_{||}\cos\theta + c_\perp \sin\theta \quad ...1$$

$$l_\theta \propto l_{||}\cos^2\theta + l_\perp \sin^2\theta \quad ...2$$

$$\Delta k'_{pe_\theta} \propto (l_\perp - l_{||})\sin 2\theta \quad ...3$$

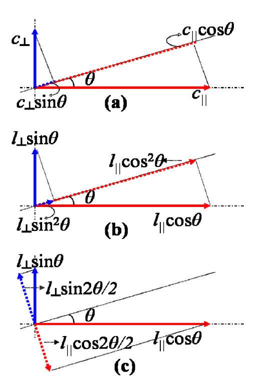

Figure 1: Diagrams showing correction schemes for (a) constant, (b) linear, and (c) oblique Nyquist ghost.

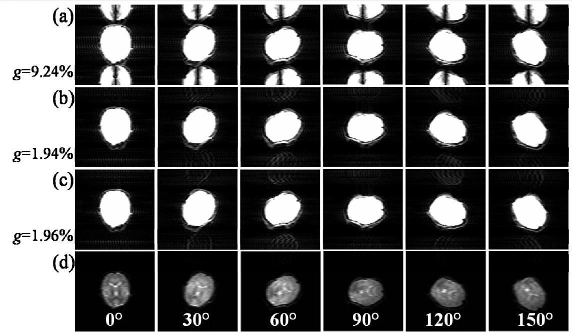

Figure 2: Individual blades of SAP-EPI (a) without phase correction, (b) after phase correction using Method A, (c) after phase correction using Method B, and (d) the image from (b) with standard window and level settings.

Results Figure 2 shows the six individual blades acquired on the human volunteer with the SAP-EPI sequence with the blade angle θ indicated in the last row. The ghost level decreases from an average of 9.24% before the phase correction (Fig. 2a) to 1.94% after correcting for constant and linear phase errors using Method A (Fig. 2b) and 1.96% with Method B (Fig. 2c). In Figs. 2a-c, the window and level settings were selected to highlight the Nyquist ghosts. Figure 2d shows the six blades using standard window and level settings after phase correcting using Method A. Similar results were obtained on the acetone phantom (data not shown). Due to minimal gradient anisotropy on the 3T scanner, oblique blades did not show substantial ONG. For a blade showing the ONG, Fig. 3 demonstrates the decrease of this ghost from 2.02% before (Fig. 3a) to 1.68% after (Fig. 3b) applying the ONG correction. Figure 3c shows the blade using standard window and level settings after all Nyquist ghost corrections.

Discussion and Conclusions We have demonstrated that the proposed technique can accurately synthesize the constant and linear phase errors for any arbitrary blade orientation in SAP-EPI based on only two reference scan measurements. This technique performed equally well when compared with the approach relying on time-consuming, blade-specific reference scans. This technique has resulted in a 33% reduction in the total scan time when the total number of blades acquired was 6, but considerably more scan time reduction occurs with an increased number of blades. Although the technique has been described and demonstrated using the axial plane as an example, it can be generalized to a blade acquired in any arbitrary plane or in 3D mode. In a more general case, reference scans may need to be acquired along two or three physical gradient axes that are involved in blade acquisition. Lastly, an important feature of the proposed technique is its capability of removing the ONG, thus unifying constant and linear phase correction along the readout direction, and ONG phase correction along the phase-encoding direction.

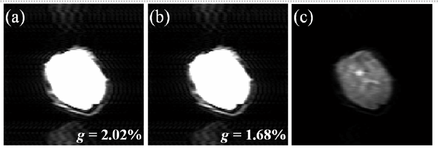

Figure 3: A single-blade image of SAP-EPI: (a) after constant and linear phase correction using Method A, (b) after correcting for oblique Nyquist ghost and, (c) the image from (b) at normal window and level settings.

References (1) Skare, *et al.*, MRM, 2006, 55: 1298-1307. (2) Wong, *et al.*, MRM, 2005, 54: 1232-1240. (3) Pipe, MRM, 1999, 42: 963–969. (4) Maier, *et al.*, US Patent 5151656, 1992. (5) Aldefeld, *et al.*, MRM, 1998, 39: 606-614. (6) Zhou, *et al.*, ISMRM Abstracts, 1996, p. 386. (7) Zhou, *et al.*, US Patent 5672969, 1997. (8) Reeder, *et al.*, MRM, 1999, 41: 87-94.