Effective removal of aliasing artifacts in interleaved diffusion weighted EPI using integrated 2D Nyquist correction and multiplexed sensitivity encoded reconstruction

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Target Audience: Researchers and clinicians who are interested in high-quality and high-resolution DWI with minimal artifact

Purpose: High-resolution DWI can be achieved by using recently developed interleaved DWI protocols. In addition to minuscule motion induced aliasing artifacts, interleaved EPI based DWI data are also susceptible to Nyquist artifacts originating from gradient waveform imperfections. Since the Nyquist artifact mainly results from gradient-induced phase errors along the readout direction, 1D Nyquist correction is routinely used for single-shot and interleaved DWI. However, in many cases (e.g., oblique-plane EPI), the Nyquist artifacts due to phase errors along the phase-encoding direction are significant, which can only be suppressed with 2D Nyquist correction methods[1-3]. Unfortunately, existing 2D Nyquist correction procedures are not compatible with interleaved DWI data (see the Theory section for details). To address this limitation, here we report a novel integrated approach to simultaneously remove 2D Nyquist artifact and shot-to-shot phase variations in interleaved and high-resolution DWI data.

Theory and methods: Figure 1 shows an example illustrating the limitation of existing 2D Nyquist correction methods. First, uncorrected 4-shot interleaved DWI data (Fig 1a) are affected by aliasing artifacts resulting from both shot-to-shot phase variations and Nyquist artifacts. Second, after 1D Nyquist artifact correction, the Nyquist artifact is partially suppressed while the motion-induced aliasing artifact remains (Figure 1b). Third, when further performing 2D Nyquist correction (originally designed for full-FOV EPI artifact removal) the Nyquist artifacts in certain regions are suppressed, but undesirable artifacts appear in other regions (arrow: Figure 1c). The artifacts due to inappropriate 2D Nyquist correction remain in the interleaved DWI data after shot-to-shot phase variations are corrected with the multiplexed sensitivity encoding (MUSE) algorithm[4] (Figure 1d). These artifacts can be removed with our new approach:

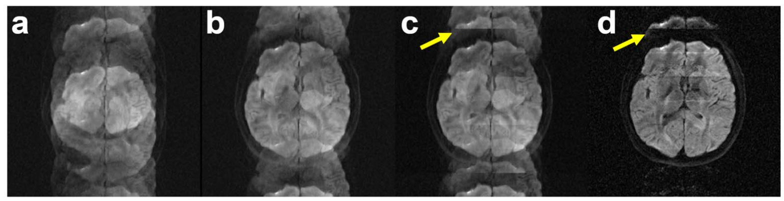

Fig.1 Illustrating the limitation of the conventional 2D Nyquist correction: a) uncorrected 4-shot DWI, b) 1D Nyqust corrected 4-shot DWI, c) 2D Nyquist corrected 4-shot DWI, and 4) MUSE reconstruction of the 2D Nyquist corrected 4-shot DWI.

<u>*First*</u>, both 1D and 2D Nyquist correction parameters were derived from T2 weighted interleaved-EPI. <u>*Second*</u>, 1D Nyquist correction was applied to interleaved DW-EPI data to minimize phase errors along the readout direction. <u>*Third*</u>, 1D corrected interleaved DWI data were then processed with an integrated reconstruction algorithm, comprising six steps: 1) images free from motion-related artifacts were reconstructed from each segment using the conventional SENSE algorithm; 2) shot-to-shot phase variations were calculated from images produced in step 1 and then spatially smoothed; 3) the odd and even echoes from each of EPI segments were further separated (Figure 2); 4) the odd-even-echo separated interleaved EPI data (step 3), the known coil sensitivity profiles, shot-to-shot phase variation information (step 2), and 2D Nyquist correction parameters were all incorporated into a mathematical framework that jointly solves the unknown magnitude source signals of overlapping voxels from all EPI segments, producing a final set of images without Nyquist ghost and aliasing artifacts.

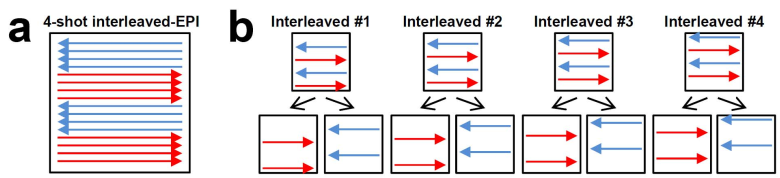

Fig.2 a) k-space acquisition scheme for 4-shot interleaved-EPI. b) The odd and even echoes are separated in each segment to produce a pseudo eight-segment interleaved-EPI data set, so that 2D Nyquist correction can be appropriately incorporated.

Three sets interleaved DWI data (*b*=0 and *b*=800 s/mm^2) were acquired from a 3T MRI scanner using an 8-channel coil, using 1) 4-shot DW-EPI in sagittal plane, 2) 4-shot DW-EPI in oblique axial plane, and 3) 8-shot interleaved DW-EPI in oblique axial plane. Since the shot-to-shot phase variation cannot be inherently measured from an 8-shot DWI scan, a parallel navigator echo (*R*=4) was used to measure shot-to-shot phase variation. The acquired data were processed with 1) the new integrated method and 2) the conventional approach, and the results were compared.

Results and Discussion: Figure 3 shows the interleaved DWI images acquired with 4-shot EPI in sagittal plane (a,d), 4-shot EPI in oblique axial plane (b,e), and 8-shot navigated EPI in oblique axial plane (c,f). It can be seen that residual artifacts in conventional 2D Nyquist corrected images (a, b, c) can all be eliminated with our new integrated algorithm (d, e, f).

The new integrated method can simultaneously eliminate aliasing artifacts resulting from both 2D Nyquist artifacts and shot-to-shot phase variations in interleaved DW-EPI data. The developed method is particularly useful for oblique-plane and sagittal-plane EPI, for which 1D Nyquist correction is insufficient due to more significant eddy current cross terms. Our experimental data demonstrate that the developed method is compatible with interleaved EPI of different segment numbers (e.g., 4 and 8 in our studies), and is effective for data with and without navigator echoes.

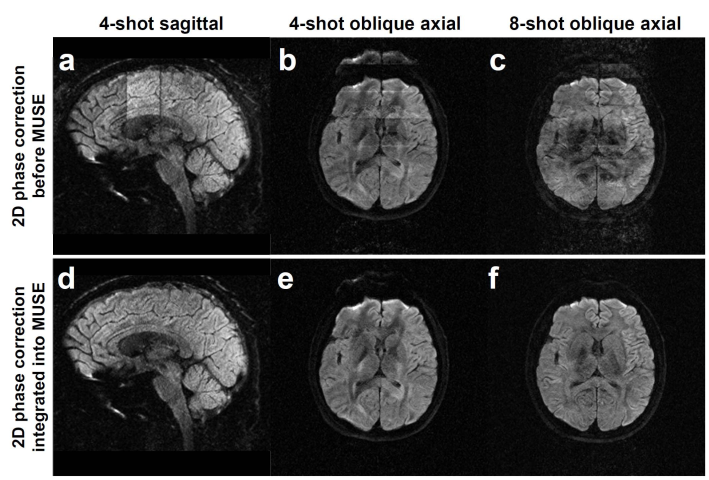

Fig. 3: Comparison of interleaved DWI quality obtained with the conventional 2D Nyquist correction (a to c) and the new method (d to f)

References: [1] MRM(51);1247, 2004. [2] MRM(64);1800, 2010. [3] MRM(66);1057, 2011. [4] Neuroimage(72);41, 2013.