On the application of phase correction and use of k-space entropy in partial Fourier diffusion-weighted EPI

S. J. Holdsworth[1], S. Skare[1], and R. Bammer[1]

[1]Lucas MRS/I Center, Stanford University, Stanford, CA, United States

Introduction: It is well-known that diffusion-weighted (DW) imaging is very sensitive to the effects of brain motion, even in single-shot (ss)-EPI [1-4]. While the extent of rigid body motion can be minimized through patient compliance and by securing the patient's head, pulsatile brain motion is ubiquitous and can be significant. Pulsatile brain motion that occurs during the application of the DW gradients can result in the dispersion of *k*-space, corresponding to signal dropout and shading in the image domain. Severe brain motion may yield a *k*-space completely corrupted by brain motion [4].

Typically, partial Fourier (PF) encoding in the phase-encoding direction is used to reduce the echo time in DW-ssEPI. Here, the number of 'overscans' is used to denote how many extra lines of *k*-space are acquired past the *k*-space center. If *k*-space is dispersed in the case of pulsatile brain motion, the number of overscans acquired may not be enough to encode some of the dispersed signal and considerable information may be lost. In addition, the lack of phase information provided by the small central strip of *k*-space used for PF reconstruction may result in artifacts in the final image. This abstract shows that phase correction applied prior to partial Fourier reconstruction in ss-EPI is helpful for recovering signal lost in cases where *k*-space is corrupted by brain motion.

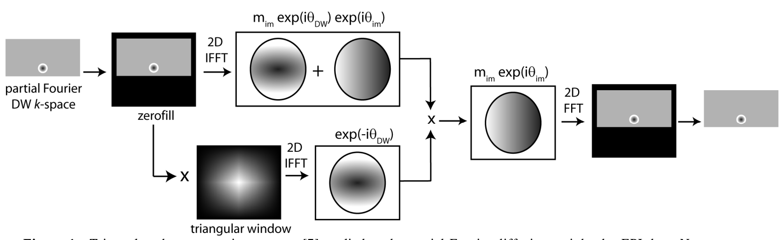

Figure 1: Triangular phase correction process [7] applied to the partial Fourier diffusion-weighted ssEPI data. Note that this process is similar to [8], however is faster with the use of zerofilling (rather than POCS).

Using the same *k*-space from several repetitions of a DW-ssEPI scheme, we explore the use of *k*-space entropy [5] as a metric to identify *k*-space corrupted by non-linear brain motion; the use of peripheral cardiac gating and non-gating; phase correction applied before both homodyne and POCS reconstruction; as well as the number of overscans that should be used to avoid significant artifacts due to pulsatile brain motion.

Materials & Methods: A healthy volunteer was scanned on a 3T whole-body GE EXCITE system (Waukesha, WI, USA, 40 mT/m, SLR = 150 mT/m/s) with an 8-channel head coil. Data were acquired by repeating an EPI diffusion scheme 150 times along the S/I direction (the direction most sensitive to pulsatile motion [6]). This scheme was repeated both with and without peripheral cardiac gating. A target resolution of 128 x 128 was used, a TR = 3 s (or 3 RR intervals and minimum trigger delay for the gated acquisition), R = 3, b = 1000 s/mm^2, and 21 slices with a thickness of 5mm. Full Fourier data were acquired – and this data was used to test various overscans. The entropy of *k*-space was used to determine the correlation between entropy and the extent of non-linear motion due to brain pulsation. Corrupted *k*-space identified by the entropy measure was then reconstructed using the following number of overscans: 8, 16, and 32. Each dataset were phase corrected using a triangular windowing approach [7] modified for partial Fourier data (Fig. 1). The phase correction approach corrects for any low spatially varying linear and non-linear motion with the use of a low resolution phase-map extracted from the center strip of *k*-space [7]. This approach was applied before both POCS [9] and homodyne [10] reconstruction. The images were compared with the same data reconstructed without phase correction.

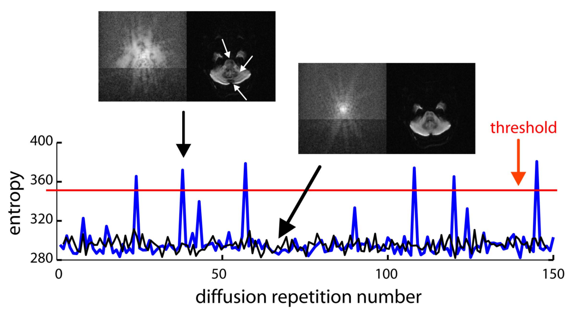

Figure 2: Plot showing the entropy of *k*-space calculated for 150 DW-ssEPI acquired in the S/I diffusion-encoding direction (b = 1000 s/mm^2, black = gated; blue = not gated). The red line shows the threshold above which *k*-space is significantly dispersed by non-linear motion (high *k*-space entropy), causing large signal dropouts in the image domain. The threshold (red line) was determined by using the mean of the entropy over the 150 repetitions + one standard deviation, and indicates the line above which these corrupted blinds have severe signal dropouts and shading in the image domain.

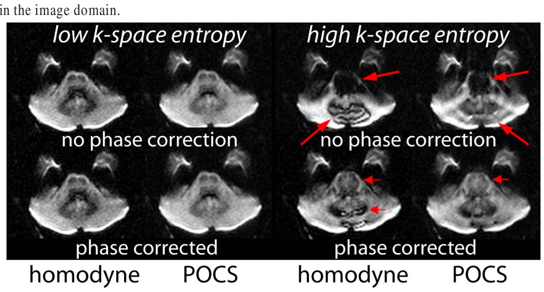

Figure 3: DW-EPI datasets with a) low *k*-space entropy, and b) high *k*-space entropy. A matrix in-plane resolution of 128 x 128 was used, slthck = 5mm, b = 1000 s/mm^2 (S/I direction). Both datasets were acquired with PF in the p/e-direction, using 8 overscans and both homodyne and POCS reconstruction. The data were also reconstructed both without (top row) and with (bottom row) phase correction. The long red arrows indicate the 'worm-like' artifacts prevalent in homodyne-reconstructed datasets corrupted by brain motion, as well as the severe signal dropouts in the brainstem in both PF methods. The small arrows indicate areas of significant improvement in the image quality due to the phase correction.

Results: Fig. 2 shows a plot of the *k*-space entropy for 150 DW-EPI repetitions calculated from one slice acquired at the base of the brain. As shown, non-linear motion causes a substantial dispersion of *k*-space data – which is paralleled with an increase in the entropy of *k*-space, and correspondingly large signal voids in the center of the image. While peripherally-gated DW-ssEPI sequences are robust against pulsatile brain motion, non-gated sequences yield corrupted *k*-space with 15% prevalence for slices located at the base of the brain (where pulsatile motion is greatest). Fig. 3 shows slices with high- and low- *k*-space entropy (taken from the highest and lowest peak in Fig. 2, respectively). Both datasets are reconstructed with POCS and homodyne (using 8 overscans), as well as reconstructed without (top row) and with (bottom row) phase correction. While there is little difference in image quality between the two types of PF reconstruction methods in the *low k*-space entropy case, the dataset with *high k*-space entropy yields significant artifacts in the image domain. For the latter, both homodyne and POCS yield a large signal void in the brain stem, with additional 'worm-like' artifacts for the homodyne reconstruction. For both reconstruction techniques, it is clear that performing the phase correction approach *before* Partial-Fourier reconstruction recovers significant signal in the brain stem for both PF methods, and has fewer worm-like artifacts for the homodyne reconstruction.

Important to note is the utility of using a larger number of overscans for avoiding brain motion artifacts [4], as shown in Fig. 4. Here, the same dataset is used, except *k*-space is trimmed to 8, 16, and 32 overscans, respectively, prior to PF reconstruction. In the case of severe non-linear motion, the increasing benefit of more overscans is evident. In addition, even in the case of 16 overscans, phase correction prior to homodyne reconstruction recovers signal in the brain stem. However, as the number of overscans approaches 32, the benefit of performing phase correction *before* PF is not clear.

Discussion: This work demonstrates *k*-space entropy as a robust metric to identify data corrupted by motion. Out of 150 repetitions of a diffusion scheme, ~15% of slices in the base of the brain (b = 1000 s/mm^2, S/I direction) revealed elevated k-space entropy which closely correlated with the extent of signal dropout and image artifacts in the image domain. The entropy metric tended to be deterministic – either low in the case of no motion, or considerably elevated (see Fig. 2).

Perhaps the most important message is the following: to help to avoid artifacts due to brain motion, it is useful to perform phase correction on PF data before PF reconstruction. It was shown that POCS out-performs homodyne reconstruction for data corrupted by non-linear motion. Both methods help to recover lost signal, however POCS results in fewer worm-like artifacts. For both methods, consistent with [4], a larger overscan factor will yield a more robust estimation of the image phase and fewer motion-related image artifacts. Used in conjunction with phase correction prior to PF reconstruction, we recommend using a minimum number of overscans of 16 to help avoid these image artifacts. Whilst the cases shown in the figures are the most extreme cases of non-linear motion we saw in our experiments, in some cases motion may be so severe (particularly when there is significant motion in the through-plane direction) that *k*-space may have to be reacquired.

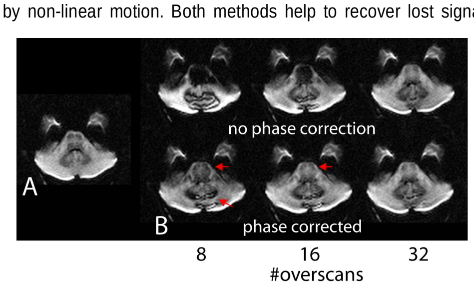

Figure 4: DW-EPI (b = 1000 s/mm^2, S/I direction) datasets acquired at an in-plane resolution of 128 x 128 showing: A) Low *k*-space entropy for reference (full Fourier data). B) Severely motion corrupted data reconstructed with various overscans both *without* phase correction (top row), as well as *with* phase correction performed prior to homodyne reconstruction. The red arrows indicate areas with significantly improved image quality.

References: [1] Norris DG. JMRI 2001;13:486–495. [2] Wedeen VJ. MRM 1994;32:116-120. [3] Butts K. MRM 1996;35:763-770. [4] Storey P. MRM;57(3):614-619. [5] Shannon CE. Weaver W. Uni. Illinois Press; 1963. [6] Wirestam R. JMRI 1996;6(2):348-355. [7] Pipe J. MRM 2002;47(1):42-52. [8] Holdsworth SJ. ISMRM 2008;4. [9] Liang ZP. Rev MRM 1992;4:67-185. [10] Noll DC. IEEE Trans. Med. Imag. 1991;10(2):154. **Acknowledgements:** This work was supported in part by the NIH (2R01EB002711, 1R01EB008706, 1R21EB006860), the Center of Advanced MR Technology at Stanford (P41RR09784), Lucas Foundation, and the Swedish Research Council (K2007-53P-20322-01-4).