THE MAGNITUDE POINT SPREAD FUNCTION IS AN INADEQUATE MEASURE OF T_2^*-BLURRING IN EPI

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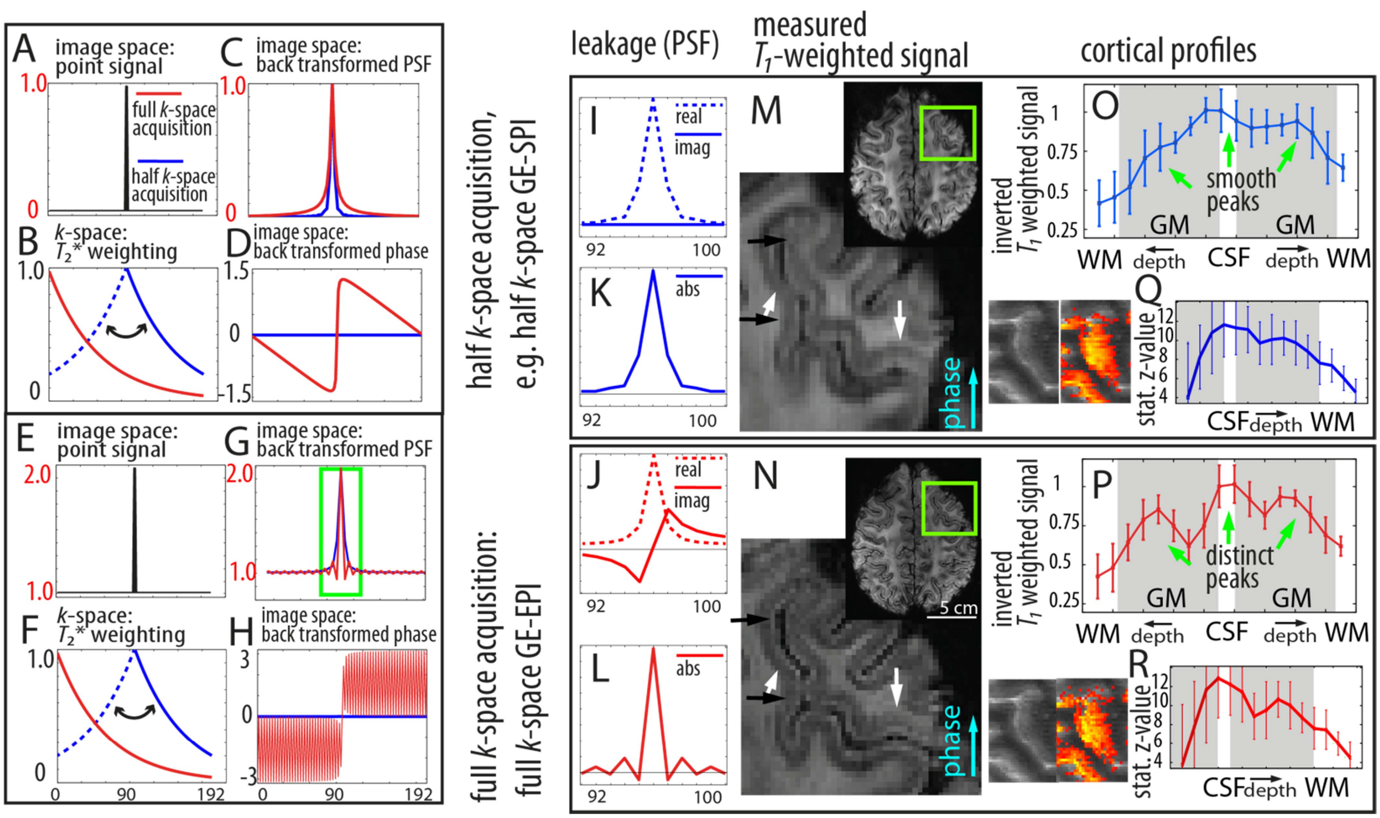
Target audience: Researchers interested in high resolution fMRI, layer-dependent fMRI, and high field fMRI.

Purpose: The magnitude point spread function (PSF) is widely used to describe the inherent blurring of magnetic resonance images. The T_2^*-based attenuation during echo planar imaging (EPI) can broaden the PSF of the resulting images in the phase encoding direction [1,2,3]. It was estimated that this T_2^*-blurring is stronger for full *k*-space acquisition in GE-EPI compared to half-*k*-space GE-EPI (partial-Fourier acquisition) and to SE-EPI [1,2,3]. The goal of this study is to demonstrate that the conventional application of estimating the width of the magnitude PSF describes the T_2^*-blurring in EPI inadequately, and to show how it can be improved. Theoretical and experimental evidence is provided that full *k*-space GE-EPI gives superior localization, as compared with half *k*-space GE-EPI and SE-EPI.

Methods: The effect of T_2^*-attenuation during the EPI readout was theoretically investigated in two ways: 1) conventional magnitude PSF estimation [1,2,3], where only one voxel is assumed to differ from zero (Delta function in Fig. A). The corresponding signal distribution in *k*-space is then weighted with the T_2^*-decay for full *k*-space GE-EPI and half GE-EPI/SE-EPI (Fig. B), respectively (dotted: mirrored in GE-EPI, acquired in SE-EPI). The back-transformation into image space provides the PSF (Fig. C) and the phase distribution (Fig. D) of the EPI signal. 2) The same estimation was additionally done for a more realistic situation resembling edges/contrast: namely, that only one voxel has a signal different from a finite background signal (Fig. E). This example is introduced to show the different effect of the complex PSF compared to the magnitude PSF. The same T_2^*-decay was introduced as described above (Fig. F) and the corresponding T_2^*-blurring in image space was calculated (Figs. G/H). In addition to these theoretical calculations, the T_2^*-blurring was investigated in vivo with the following acquisition parameters: 7 T, inversion-recovery GE-EPI, matrix 192 × 192, echo spacing = 0.6 ms, nominal resolution 0.8 × 0.8 × 2 mm^3. Grappa 2, TE = 49 ms. This long TE was chosen to provide a worst-case scenario with considerable T_2^*-decay. Two different readout strategies were used to estimate the different T_2^*-blurring: full *k*-space acquisition (readout window = 110 ms) and half *k*-space acquisition (readout window = 60 ms) with the same TE. In order to correct for phase inhomogeneities in the half *k*-space acquisition, 8% of the *k*-space lines were acquired symmetrically, across the center of *k*-space.



Results: Conventional estimation of the PSF associated with T_2^*-blurring (one voxel ≠ 0; Fig. A) and full *k*-space GE-EPI gives a larger FWHM compared to half *k*-space EPI/SE-EPI PSF (Fig. C). Note that due to the step in the phase distribution (Fig. D), the real and the imaginary part of the PSF have a narrower FWHM in full *k*-space GE-EPI than in half *k*-space EPI/SE-EPI (Figs. I-LJ). For the adapted way of estimating T_2^*-blurring (Fig. E), the magnitude PSF of full *k*-space GE-EPI has a narrower FWHM than that of half *k*-space EPI/SE-EPI (Fig. G). This is a result of positive and negative interference of signal from adjacent voxels depending on their phase. The experimental data confirms that full *k*-space acquisition appears to give better spatial specificity in the phase encoding direction than half *k*-space acquisition (Figs. M/N). Intracortical anatomical layers are blurred in the phase-encoding direction (white arrows), but not in the read direction (black arrows) for the half *k*-space GE-EPI (Fig. M). The smoothness in the phase encoding direction was quantified with (SMOOTHEST) [4], to be 0.6 mm (FWHM) for the full *k*-space GE-EPI data and 0.9 mm for the half *k*-space EPI data, respectively. The discriminability of the intra-cortical layer-dependent signal peaks (Figs. O and P) confirms this (green arrows). Correspondingly, during a finger tapping task, the functional profiles deliniated layer-dependent responses with higher effective resolution for the full *k*-space GE-EPI scheme compared to the case where T_2^*-attenuation is symmetric in *k*-space (Figs. Q/R).

Discussion: The data shown here suggest that asymmetric T_2^*-blurring in full *k*-space GE-EPI provides higher effective resolution compared to symmetric T_2^*-blurring in half *k*-space GE-EPI or SE-EPI acquisition. All investigations of the PSF refer to the effect of T_2^*-decay during *k*-space sampling. Independent of the T_2^*-blurring, there are other advantages and disadvantages: The longer acquisition window of full *k*-space acquisition compared to half *k*-space acquisition is accompanied with longer minimal TE and higher motion sensitivity. On the other hand, due to the acquisition of redundant information in symmetric *k*-space, full *k*-space GE-EPI achieves a higher SNR at the same TE.

Conclusion: The conventional usage of the width of the magnitude PSF to estimate T_2^*-blurring can be misleading. In order to take into account that MRI produces complex signals, which can add up constructively or destructively, the PSF must be considered in the complex domain (Figs. I-L) [5]. We show here that full *k*-space GE-EPI acquisition has a higher effective resolution than half *k*-space GE-EPI or SE-EPI due to less intense low-pass weighting of *k*-space.

References: [1] Jesmanowicz et al., MRM, 1998; [2] Hyde et al., MRM, 2001; [3] Hetzer et al., MRM, 2011; [4] Nichols et al., FMRIB technical report TR08TNI, 2008; [5] Qin, MRI, 2012. Funded by EU through Marie Curie HiMR ITN (PITN-GA-2012-316716).