# On the influence of zero padding on the non linear operations of quantitative susceptibility mapping

Sarah Eskreis-Winkler[1], Dong Zhou[2], Tian Liu[3], Ajay Gupta[2], Susan Gauthier[2], Yi Wang[2], and Pascal Spincemaille[2]
[1]*Weill Cornell Medical College, New York, NY, United States,* [2]*Weill Cornell Medical College, New York, United States,* [3]*MedImageMetric, LLC, New York, United States*

**Target audience:** Those interested in improving QSM quality
**Purpose:** To explore the utility of zero padding complex gradient echo (GRE) data prior to performing quantitative susceptibility mapping (QSM). Zero padding improves image visualization without increasing image resolution (1,2). Here, we seek to demonstrate that an interaction between (a) the zero padding of the GRE data and (b) the nonlinear steps typically used in QSM, results in an improved final susceptibility map.
**Methods:** In this work, "zero padding" was used as a shorthand for image interpolation by zero-padding in fourier space. **Data acquisition**. A multi-echo 3D gradient echo (GRE) scan was acquired in a healthy subject at 3T (GE Healthcare, matrix size: 240x194x60, voxel size: 0.9375x0.9375x2mm, 11 echoes, $TE_1$/ $\Delta TE$: 4.5/4.8ms, flip angle 20, bandwidth 62.5). 20 Multiple Sclerosis patients were scanned with the same GRE sequence (matrix size: 512x512x50, voxel size: 0.47x0.47x3mm, 11 echoes, $TE_1$/ $\Delta TE$ /TR: 4.5/4.8/57.9ms, flip angle 20, bandwidth 62.5). **Post-processing** Low resolution scans (LR) were simulated by discarding the outer half of k-space of the high resolution (HR) data in all 3 dimensions. QSM was reconstructed by phase unwrapping, field map estimation, background field removal (3) and dipole inversion (MEDI) (4). For each subject, the following QSMs were reconstructed: (1) High resolution QSM: The unmodified HR GRE data were used to generate a "gold standard" QSM. (2) Pre Zero Padded QSM: LR data were zero padded to achieve a matrix size equivalent to that of the HR data, followed by QSM. (3) Mid Zero Padded QSM: LR data were used to generate a local field map, which was then zero padded, followed by MEDI. (4) Post Zero Padded QSM: LR data were used to generate a QSM image, which was then zero padded. **Image Analysis** For each MS patient, a neuroradiologist assigned image quality scores to the pre-, mid- and post- zero padded QSM images. Apparent spatial resolution was calculated by computing the point spread function (PSF) of the pre-, mid-, and post-zero padded QSM images with respect to the high resolution QSM using a deconvolution method. A relative error was calculated over the whole image and over ROIs encompassing MS lesions. A correlation coefficient with the HR field map was calculated for each method.
**Results** For the healthy subject, results are shown in Figure 1. The relative errors over the whole image of the pre-, mid-, and post-zero padded methods as compared to the high resolution QSM were 0.39, 0.47 and 0.51 respectively. The apparent resolution for the pre-zero padded, mid-zero padded, and post-zero padded methods, as measured by the full width half maximum of the PSFs, were 1.30, 1.90 and 2.10 voxels along $x$, 1.55, 2.55 and 2.60 voxels along $y$, and 1.15, 1.80, and 2.15 voxels along $z$ respectively. For the MS patient whole brain data, the relative error (0.57±0.07) over the whole image of the pre-zero padded QSM was less than that of the mid-zero padded QSM (0.76±0.09; p= 6e-17), which was less than that of post-zero padded QSM (0.79±0.09; p=2e-4). The apparent spatial resolution of the pre-zero padded QSM (1.27±0.18 voxels) was higher than that of the mid-zero padded QSM (1.72±0.22; p=5e-19), which was higher than that of the post-zero padded QSM (1.84±0.20; p=3e-7). For the MS lesions, pre-zero padded QSM image quality scores (2.56±0.63) were higher than both the mid-zero padded scores (2.02±0.83; p=4e-3), and the post-zero padded scores (1.77±0.92, p=9.7-5), with the difference between the last n.s (p=0.57). Two MS lesions magnified in Figure 2 illustrate how pre-zero padded reconstructions more accurately depict lesion geometry than mid- and post-zero padded reconstructions. Furthermore, the relative errors of pre-zero padded lesion ROIs (0.44±0.24) were lower than those of the mid- zero padded lesions (0.58±0.32; p=9e-4), which were lower than those of the post-zero padded (0.65±0.40; p=4e-6).
For the field map k-space analysis, the correlation coefficient between the k-space of the high resolution field map and the k-space of the pre-zero padded field map (r=0.75) was higher that of the post-zero padded field map (r=0.53). See Figure 3.
**Discussion:** Our results indicate that QSM image quality, apparent resolution, and accuracy all increase when zero padding is performed on the complex GRE data before field mapping and QSM reconstruction – pre-zero padding – as compared to when zero padding is performed after field mapping but before QSM reconstruction or after QSM reconstruction. Furthermore, zero padding prior to phase unwrapping and field map estimation results in an estimated field map with non-zero high frequency k-space data that is a closer approximation of the "true" high frequency field map k-space. This may be explained by thinking about these nonlinear steps as introducing prior information, e.g. field map estimation imposes a linear phase evolution over echo time in each voxel.
**Conclusion:** Zero padding of the complex GRE data prior to the nonlinear steps of QSM improves image accuracy and increases apparent image resolution. It also provides better delineation of MS lesion geometry, which may improve lesion subclassification and disease monitoring in MS patients.

**References**:1.Du Y, et al. *JMRI*. 1994; 4(5):733-41.2.Parker D, et al., *MRM* 1995;33(2): 156-62. 3. Liu T, et al., *NMR in biomedicine* 2011;24(9):1129 -1136. 4. Schweser, F., et al. *NeuroImage* 2011; 59(3):2789-2807.

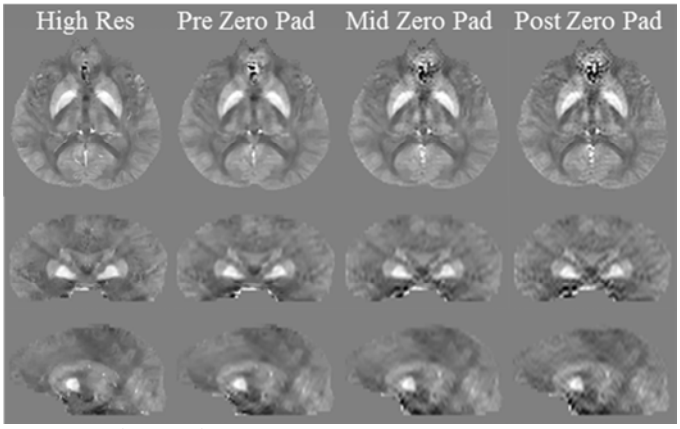

Figure 1: Influence of zero padding on QSM with comparison to a true high resolution QSM. Pre zero padding had the highest image quality. Markedly increased streaking artifacts were seen with post zero padding.

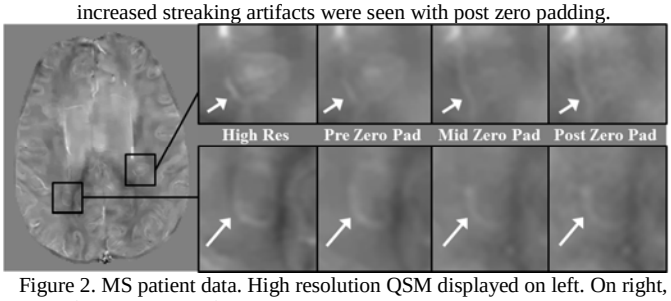

Figure 2. MS patient data. High resolution QSM displayed on left. On right, magnified MS lesions from the various zero padded QSM methods illustrate that lesion geometry may be better depicted in pre-zero padded QSM reconstructions compared to mid- and post-zero padded QSM

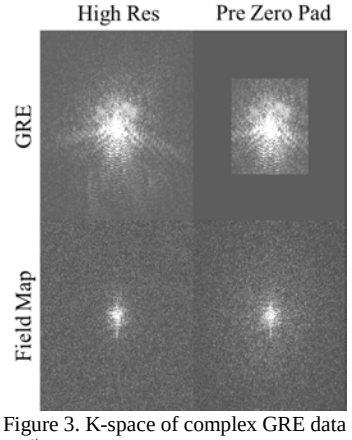

Figure 3. K-space of complex GRE data (1st echo, top) and field map (using all echoes, bottom). Low frequency k-space is identical with high frequency k-space equal to zero for LR. However, the corresponding field map exhibits non-zero high frequency k-space information