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On the influence of zero-padding on the nonlinear operations in Quantitative Susceptibility Mapping

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ABSTRACT

Purpose: Zero padding is a well-studied interpolation technique that improves image visualization without increasing image resolution. This interpolation is often performed as a last step before images are displayed on clinical workstations. Here, we seek to demonstrate the importance of zero padding before rather than after performing non-linear post-processing algorithms, such as Quantitative Susceptibility Mapping (QSM). To do so, we evaluate apparent spatial resolution, relative error and depiction of multiple sclerosis (MS) lesions on images that were zero padded prior to, in the middle of, and after the application of the QSM algorithm.
Materials and Methods: High resolution gradient echo (GRE) data were acquired on twenty MS patients, from which low resolution data were derived using k-space cropping. Pre-, mid-, and post-zero padded QSM images were reconstructed from these low resolution data by zero padding prior to field mapping, after field mapping, and after susceptibility mapping, respectively. Using high resolution QSM as the gold standard, apparent spatial resolution, relative error, and image quality of the pre-, mid-, and post-zero padded QSM images were measured and compared.
Results: Both the accuracy and apparent spatial resolution of the pre-zero padded QSM was higher than that of mid-zero padded QSM ($p<0.001$; $p<0.001$), which was higher than that of post-zero padded QSM ($p<0.001$; $p<0.001$). The image quality of pre-zero padded reconstructions was higher than that of mid- and post-zero padded reconstructions ($p=0.004$; $p<0.001$).
Conclusion: Zero padding of the complex GRE data prior to nonlinear susceptibility mapping improves image accuracy and apparent resolution compared to zero padding afterwards. It also provides better delineation of MS lesion geometry, which may improve lesion subclassification and disease monitoring in MS patients.

1. Introduction

Quantitative susceptibility mapping (QSM) is a recently developed contrast technique that depicts and quantifies magnetic sources in the body, such as iron, deoxyhemoglobin, calcium, and contrast agents [1,2]. Several clinical applications of QSM, such as visualization of multiple sclerosis (MS) lesion geometry, require high spatial resolution.

In current practice, reconstructing high spatial resolution QSM necessitates 1) a longer scan time to acquire high resolution MRI data, and 2) deconvolution using a high resolution dipole kernel, which reduces the discretization error. This is because in previous work, magnetic susceptibility maps are solved at the same resolution as the acquired MRI data [1,3–5].

To avoid lengthening scan time, this paper explores the utility of zero padding the complex gradient echo (GRE) data prior to performing susceptibility mapping. Zero padding is a well-studied interpolation technique that improves image visualization without increasing image resolution [6–12]. It is generally applied as a final step before images are displayed on clinical workstations. Here we seek to demonstrate that when there are non-linear post-processing steps, such as QSM, it is important to zero pad prior to rather than after performing the QSM algorithm. The major nonlinear steps

Abbreviations: QSM, Quantitative susceptibility mapping; GRE, gradient echo; PDF, Projection onto Dipole Fields; MEDI, morphology enabled dipole inversion; ROI, region of interest; PSF, point spread function; FWHM, full-width-half-maximum; PCOS, projection onto convex sets.

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within QSM using MEDIN [13] are temporal and spatial phase unwrapping, nonlinear field map fitting and L1 regularized dipole field fitting.

In this paper, we demonstrate that zero padding of the complex GRE data prior to, rather than following, nonlinear QSM results in a susceptibility map with increased apparent spatial resolution, decreased relative error, and improved depiction of MS lesions as compared to post-zero padding (i.e., zero padding of the susceptibility map reconstructed directly from low resolution data using a low resolution dipole kernel). Additionally, we explore the effect of zero padding at various stages of the QSM algorithm. Since the QSM algorithm is non-linear, the zero padding operation and the QSM algorithm are not commutative; it is therefore instructive to explore at which point it is best to perform the zero padding operation.

2. Materials and methods

Low resolution complex GRE data were simulated by cropping the k-space of the high resolution data. Pre-, mid- and post-zero padded QSM images were reconstructed from these low resolution data using a zero padding step at the beginning, middle, and end of the QSM algorithm respectively (see below for details). These reconstructions were compared using high resolution QSM, obtained from the original high resolution data, as the gold standard.

To further evaluate the k-space effects of zero padding before versus after non-linear operations, the k-space of field maps derived from pre- and post- zero padded low resolution complex GRE data were compared to the k-space of the field map derived from high resolution complex GRE data.

2.1. Data acquisition

2.1.1. Healthy subject

A multi-echo 3D gradient echo scan was acquired using a single-channel head coil on a 3 T scanner (GE Healthcare, Waukesha, WI) in accordance with our Institutional Review Board (IRB) (matrix size: 240×194×60, voxel size: $0.9375 \times 0.9375 \times 2$ mm^3, 11 echoes, $TE_1/\Delta TE/TR$: 4.5/4.8 ms, flip angle 20 degrees, bandwidth 62.5 kHz).

2.1.2. Multiple sclerosis patients

This retrospective study was approved by our IRB. We reviewed the MRI database in our institution's clinical imaging database and identified 20 patients who met both of the following criteria: a) clinically confirmed MS patients; b) underwent an MR scan including a 3D multiple-echo GRE sequence using a 8-channel head coil (matrix size: 512×512×50, voxel size: $0.47 \times 0.47 \times 3$ mm, 11 echoes, $TE_1/\Delta TE/TR$: 4.5/4.8/57.9 ms, flip angle 20 degrees, bandwidth 62.5 kHz) as part of the current standard-of-care at our institution during October 2013. MRI was performed on a 3T scanner (GE Healthcare, Waukesha, WI, USA). All 20 patients (6 male, 14 female, aged 32–69, 46 ± 10 years) had expanded disability status scale ranging from 0 to 8 (median: 1.25) and disease duration ranging from 3 to 26 (11 ± 7) years. All patients were treated with a standard FDA immunomodulatory therapy.

2.2. Post-processing

For the healthy subject and the MS patients, low resolution scans were simulated by discarding the outer half of the complex k-space in all three dimensions.

To reconstruct QSM images, phase images were temporally unwrapped, a field map was generated by performing a voxel-by-voxel non-linear least squares fitting of the complex signal over TE, and the resultant field map was spatially unwrapped. Next, the background field, defined as the magnetic field generated by susceptibility sources outside the region of interest (ROI), was removed by applying Projection onto Dipole Fields (PDF) [14], obtaining the local field. The ROI was set to the brain as obtained by the BET segmentation algorithm [15]. Using the local field, the magnetic field-to-susceptibility-source inverse problem was solved using morphology enabled dipole inversion (MEDI), which uses an L1 regularization term to promote similarity of edges between the QSM solution and the GRE magnitude image [13,16–18].

For each subject, the following QSM reconstructions were performed:

1. High resolution QSM: The unmodified high resolution complex GRE data were used to generate a “gold standard” QSM.
2. Pre-zero padded low resolution QSM: Low resolution complex GRE data were zero padded to achieve a matrix size equivalent to that of the high resolution data, followed by QSM.
3. Mid-zero padded low resolution QSM: Low resolution complex GRE data were used to generate a low resolution local field map using the same methods described above. This field map was then zero padded, followed by dipole inversion using MEDI.
4. Post-zero padded low resolution QSM: Low resolution complex GRE data were used to generate a QSM image, as described above, followed by zero-padding to achieve a matrix size equivalent to that of the high resolution data.

All QSM images therefore had the same matrix size, which was 8 times that of the low resolution QSM image before zero padding. To avoid display interpolation issues, only QSM images of the same size, as described in the above, were considered for comparison.

2.3. K-space field map post-processing

For the healthy subject, k-space of the following field maps was reconstructed:

1. High resolution field map: The unmodified high resolution complex GRE data were used to generate a “gold standard” field map
2. Pre-zero padded low resolution field map: Low resolution complex GRE data were zero padded to achieve a matrix size equivalent to that of the high resolution data, followed by field map estimation.
3. Post-zero padded low resolution field map: Low resolution complex GRE data were used to generate a field map followed by zero-padding to achieve a matrix size equivalent to that of the high resolution data.

2.4. Image analysis

2.4.1. Image quality score

For each MS patient, a neuroradiologist with 8 years of experience identified the three largest lesions on T2 W that were also visible on the high resolution QSM reconstruction. For each lesion, the neuroradiologist blindly assigned image quality scores to the pre-, mid- and post- zero padded QSM images using the following scale: 0: lesion was not visible; 1: the lesion was either poorly visible or differed markedly from the appearance on high resolution QSM; 2: lesion visibility was fair and generally resembled that of the high resolution QSM; 3: the lesion was well visualized and there was good geometrical agreement with the high resolution QSM. A Wilcoxon rank sum test was performed to test for statistically significant differences in image quality.

2.4.2. Apparent spatial resolution

For the healthy subject as well as for the MS patients, apparent spatial resolution was calculated for each reconstruction method by