Noise from non-cone regions in segmented k-space contributes to artifacts in Quantitative Susceptibility Mapping

Shuai Wang[1,2], Tian Liu[3], Weiwei Chen[4], Pascal Spincemaille[2], and Yi Wang[2,5]

[1]*University of Electronic Science and Technology of China, Cheng Du, Si Chuan, China, People's Republic of,* [2]*Radiology, Weill Cornell Medical College, New York, New York, United States,* [3]*MedImageMetric LLC, New York, New York, United States,* [4]*Radiology, Tongji Hospital, Tongji Medical College, Huazhong University of Science&Technology, Wuhan, Hubei, China, People's Republic of,* [5]*Biomedical Engineering, Cornell University, Ithaca, New York, United States*

INTRODUCTION: Quantitative Susceptibility Mapping (QSM) by solving the ill-posed inverse problem from the measured magnetic field to tissue susceptibility has generated increasing amount of scientific and clinical interests using many different inverse solutions (1-7). In this study attempting to sort out various inverse solutions to identify a robust QSM for clinical applications, we identify noise from non-cone regions in **k**-pace contributes to artifacts in QSM.

QSM inversion method categories: We note the forward problem from local magnetic field to susceptibility distribution in **k**-space as (8): $\psi(\boldsymbol{k}) = D(\boldsymbol{k})\chi(\boldsymbol{k})$ [Eq.1]. Here $\psi(\boldsymbol{k}) = \mathbf{F}\delta B(\mathbf{r})$, **F** is Fourier transform, $\delta B(\mathbf{r})$ is the local field measured relative to B0, $D(\boldsymbol{k})$ is the dipole kernel. We categorize QSM inversion methods as: **1) image- or r-space methods** express the reconstruction problem in the image domain only. An example is the MEDI method (3), which expresses the data fidelity in **r**-space with a nonuniform data weighting to account for the spatially varying phase noise. **2) k-space methods** express the reconstruction problem completely in **k**-space, and circumvent the division-by-zero problem near the zero-kernel cone surface ($|D(\boldsymbol{k})| < \epsilon, \epsilon \sim 0.1$, referred as the cone region) by either employing explicit threshold (7), or mimicking L'Hospital's rule to allow susceptibility vary with **k** as in Weighted K-space Derivative (WKD) (5). **3) Hybrid space methods** assume certain mathematical properties of the susceptibility map in **k**-space, **r**-space or other spaces and express the problem in hybrid spaces. An example of this is the Compressed Sensing Compensated (CSC) QSM method (6), in which the missing data in the cone region in **k**-space is recovered using Compressed Sensing.

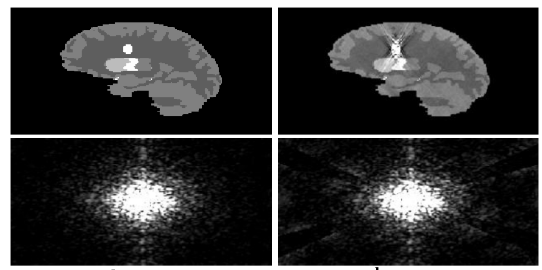

Fig 1. Images of lesion phantoms in **r**-space (top) and **k**-space (bottom). a) noise free susceptibility. b) susceptibility with noise only in the non-cone region in **k**-space.

METHODS: We first investigated the noise propagation from non-cone region in **k**-space using a Zubal-type numerical susceptibility phantom with an additional susceptibility lesion. The noise contribution to QSM artifacts (by adding SNR=80 Gaussian noise in simulated complex MRI data) from the non-cone region in k-space was singled out by using noise free accurate susceptibility values in the cone region of **k**-space. Then we evaluated the above three methods on 21 consecutive brain patients imaged on a 3T MRI system using a 3D multi-echo gradient echo sequence (20° flip, 57 ms TR, 8 echoes with a first 5.7ms TE and uniform 6.7ms ΔTE, 24cm FOV, 2mm slice, 512x512x70 matrix). An experienced neuroradiologist scored all images blinded to their reconstruction methods (1=severe artifacts/blurring; 2=moderate artifacts/ blurring; 3=no artifacts/blurring). Wilcoxon test was performed on the scores.

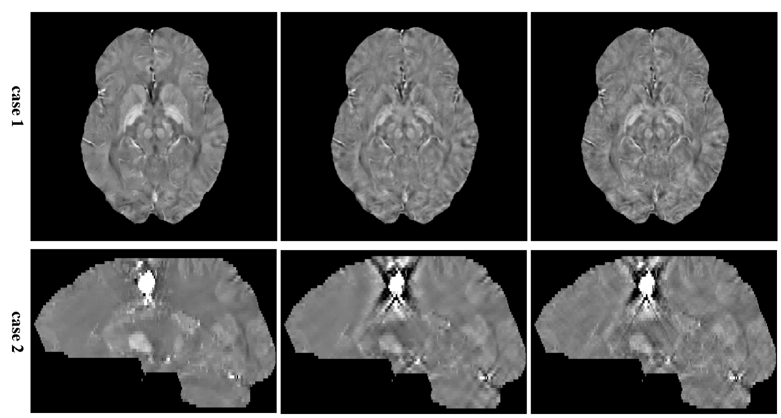

Fig 2. QSM reconstruction using MEDI (left) , CSC (middle) and WKD (right) in a patient without abnormalities (top) and a patient suffering from a brain hemorrhage

RESULTS: Noise from the non-cone region in **k**-space resulted in streaking artifacts in QSM (Fig.1). The regularization/threshold parameters in each QSM method were optimized by an exhaustive search on a subject to give the best balance between artifact suppression and apparent resolution. Two cases are illustrated in Fig.2 (top without abnormality and bottom with a hemorrhage). Eleven regions (caudate nucleus, corpus callosum, dentate nucleus, vein of galen, globus pallidus, cortical gray-white matter interface (GM-WM), optic radiation, putamen, red nucleus, substantia nigra , thalamus) plus 28 lesions were scored in the patients. The image scores (mean±std dev) of QSMs by MEDI, CSC and WKD were 2.93±0.24, 2.17±0.56 and 2.12±0.59 respectively. There were no statistically significant difference between CSC and WKD in any of the 11 brain regions (p>0.4) or lesions (p=0.85) except for the GM-WM regions (p<0.01). MEDI was superior to CSC and to WKD in every region and lesion (p<0.01).

DISCUSSION AND CONCLUSION: Fundamentally the ill-posedness of the dipole inversion is characterized by its huge condition number that generates huge noise propagation. It is known that the noise from the cone region generates severe streaking artifacts in QSM, and previous effects have been focused on address this cone region noise problem. Noise propagation from non-cone region has not been investigated to our knowledge, and we found it also contributes to streaking artifacts in QSM. The residual streaking artifacts in WKD and CSC may be explained by the lack of addressing noise propagation from non-cone region in **k**-space during the dipole inversion. The superiority of MEDI may be explained by its r-space regularization that may have addressed artifacts from all of **k**-space (and not just the cone region).

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