iLSQR: a Quantitative Susceptibility Mapping method Provided by STI Suite V2.12

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TARGET AUDIENCE: Clinicians and scientists who are interested in the application of quantitative susceptibility mapping (QSM).

PURPOSE: QSM is a method for quantifying tissue's magnetic susceptibility by solving an ill-conditioned inverse problem. Susceptibility maps reconstructed from single-orientation data often suffer from streaking artifacts that obscure structural details and small lesions. We proposed a method for estimating and eliminating streaking artifacts from the ill-conditioned k-space. Specifically, this method uses the LSQR method [1] to derive an initial mapping of magnetic susceptibility, a fast quantitative susceptibility mapping method to extract the susceptibility boundaries, and an iterative approach to determine and eliminate the susceptibility artifact from ill-conditioned k-space regions only. With a fixed set of parameters, this method provides an unbiased quantification of tissue susceptibility as compared to multi-orientation QSM reconstruction using COSMOS, and with negligible streaking artifacts. This method, named as the iLSQR method, is provided in the STI Suite 2.12, and can be downloaded at http://people.duke.edu/~cl160.

THEORY: From the normalized phase ($\psi = \varphi / \gamma\mu_0 H_0 TE$), the initial susceptibility map can be obtained by using the LSQR method:

$$FT^{-1}\{D_2 \cdot FT(W_I \cdot \psi)\} = FT^{-1}\left\{D_2 \cdot FT\left[W_I \cdot FT^{-1}\{D_2 \cdot FT(\chi_{LSQR})\}\right]\right\} \quad [1]$$

where FT means Fourier transform, W_I is the image space weighting to attenuate errors due to imperfect phase unwrapping, and D_2 can be calculated from the spatial frequency **(k)** and the field direction $\hat{\mathbf{H}}$ as $D_2 = 1/3 - (\hat{\mathbf{H}} \cdot \mathbf{k})^2 (k_x^2 + k_y^2 + k_z^2)^{-1}$.

The susceptibility boundaries were determined using a novel method called "fast QSM". First, a qualitative susceptibility contrast is calculated based on D_2:

$$\chi_{F1}(k) = sign(D_2) \cdot FT(\psi) \quad [2]$$

A discontinuity in $\chi_{F1}(k)$ around the conical surface defined by D_2=0 is expected, which is a source of streaking artifacts. To attenuate this discontinuity, the discontinuous k-space data is averaged twice along the conical surfaces:

$$\chi_{F2} = Mask \cdot FT^{-1}\{\chi_{F1}(k) \cdot W_{FS} + Filter[\chi_{F1}(k)] \cdot (1 - W_{FS})\}$$
$$\chi_{FS} = Mask \cdot FT^{-1}\{FT(\chi_{F2}) \cdot W_{FS} + Filter[FT(\chi_{F2})] \cdot (1 - W_{FS})\} \quad [3]$$

where and *Filter* represents a low-pass filtering operation to remove the discontinuity. W_{FS} is used to ensure that the "averaging" of k-space data is restricted to ill-conditioned regions. The resulting χ_{FS} shows very similar contrast to the final susceptibility with negligible streaking artifacts, and is used to determine the susceptibility boundaries.

With an initial susceptibility by LSQR, the ill-conditioned k-space defined by $M_{IC} = (|D_2(k)| < D_{2,thres})$ and susceptibility boundary weighting W_{Gi} determined using χ_{FS}, the streaking artifacts $\chi_{SA}(k)$ can be estimated using the following minimization:

$$\min_{\chi_{SA}(k)} \sum_i \left\| W_{Gi} \cdot G_i \{\chi_0 - FT^{-1}[\chi_{SA}(k) \cdot M_{IC}]\} \right\|_2 \quad [4]$$

where i = x, y and z; G_i are gradient operators. The final susceptibility is obtained by subtracting the susceptibility artifacts from LSQR-determined susceptibility:

$$\chi_{iLSQR} = \chi_{LSQR} - FT^{-1}[\chi_{SA}(k) \cdot M_{IC}] \quad [5]$$

The whole procedure was illustrated in Fig. 1.

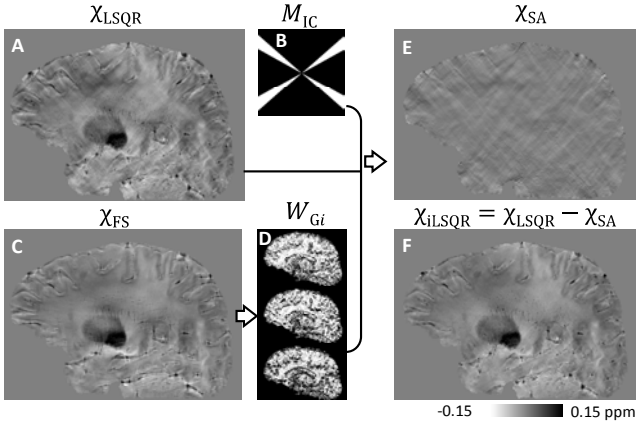

Fig. 1. Overview of the iLSQR method. A: Initial susceptibility estimate using LSQR. B: The fraction of k-space for streaking artifact estimation. C: The susceptibility map by fast QSM method for estimation of susceptibility boundaries. D: Weights determined using χ_{FS}. E: the estimated susceptibility artifacts. F: The final streaking artifact removed susceptibility map.

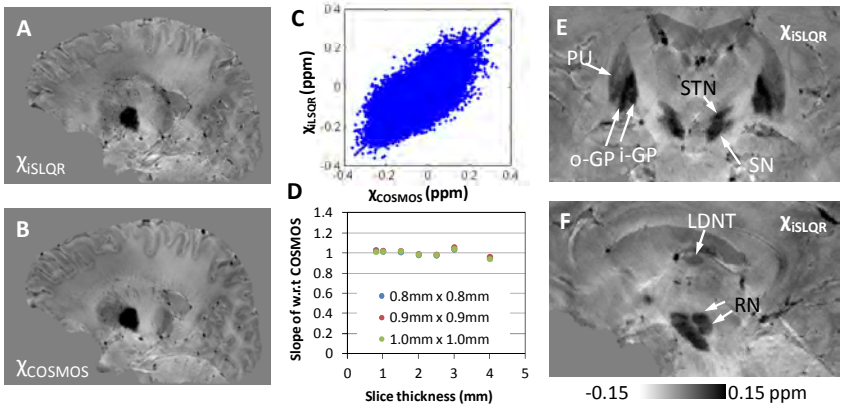

Fig. 2. Validation of the iLSQR method using COSMOS and its application for high resolution brain imaging. A and B: susceptibility map by iLSQR and COSMOS. C: Linear regression using total least squares. D: plot of slope of linear regression between iLSQR and COSMOS with different spatial resolutions. E and F: High resolution susceptibility maps by iLSQR. STN: subthalamas nucleus; RN: red nucleus; LDNT: the lateral dorsal nuclei of thalamus; iGP and oGP: the inner and outer globus pallidus; SN: substantia nigra; PU: putamen.

METHODS: *Brain Imaging*: One adult was scanned on a GE MR750 3T scanner equipped with an 8-channel head coil, using a multi-echo GRE sequence with the following parameters: flip angle = 20°, TE_1 = 5 ms, echo spacing = 4.86 ms, 16 echoes, TR = 80 ms, matrix size = 320x320x200, 0.6 mm isotropic resolution. The same scans were repeated with two different head orientations. The phase maps were filtered using the V-SHARP method [2]. Multi-orientation COSMOS reconstruction was performed as described by Liu et al [3].

RESULTS: We identified that the key parameters for iLSQR are the error tolerance for initial LSQR reconstruction, and $D_{2,thres}$ for streaking artifact removal. By setting the error tolerance to be 0.01 for iLSQR, and $D_{2,thres}$ to be 0.1, we can obtain an unbiased susceptibility mapping as compared to COSMOS, which is robust over a range of in-plane resolutions (0.8x0.8 to 1x1 mm^2) and slice thicknesses (0.8 to 4 mm) (Fig. 2D). This iLSQR allows visualization of small deep brain structures with excellent anatomical details (Fig. 2 E and F).

CONCLUSION: An iLSQR method is developed, which allows unbiased mapping of magnetic susceptibility as compared to COSMOS, effective elimination of streaking artifacts, robustness over a range of spatial resolutions and reasonable reconstruction time for routine clinical applications.

REFERENCES: [1] Li et al, Neuroimage 2011; 55:1645. [2] Li et al, NMR Biomed 2014; 2:219. [3] Liu et al, MRM 2009; 61:196.