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# A method for estimating and removing streaking artifacts in quantitative susceptibility mapping

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ABSTRACT

Quantitative susceptibility mapping (QSM) is a novel MRI method for quantifying tissue magnetic property. In the brain, it reflects the molecular composition and microstructure of the local tissue. However, susceptibility maps reconstructed from single-orientation data still suffer from streaking artifacts which obscure structural details and small lesions. We propose and have developed a general method for estimating streaking artifacts and subtracting them from susceptibility maps. Specifically, this method uses a sparse linear equation and least-squares (LSQR)-algorithm-based method to derive an initial estimation of magnetic susceptibility, a fast quantitative susceptibility mapping method to estimate the susceptibility boundaries, and an iterative approach to estimate the susceptibility artifact from ill-conditioned k-space regions only. With a fixed set of parameters for the initial susceptibility estimation and subsequent streaking artifact estimation and removal, the method provides an unbiased estimate of tissue susceptibility with negligible streaking artifacts, as compared to multi-orientation QSM reconstruction. This method allows for improved delineation of white matter lesions in patients with multiple sclerosis and small structures of the human brain with excellent anatomical details. The proposed methodology can be extended to other existing QSM algorithms.



## Introduction

The signal phase of gradient echo MRI provides much higher gray–white matter contrast than the corresponding magnitude, and contains unique information regarding deoxyhemoglobin, iron, myelin, and tissue microstructure (Duyn et al., 2007; He and Yablonskiy, 2009; Rauscher et al., 2005). Despite these promises, one intrinsic limitation is that phase value at one location depends on both the adjacent magnetic susceptibility distribution and the orientation with respect to the main magnetic field, and thus not suitable for quantitative assessment of tissues. Over the past few years, there have been growing efforts in developing quantitative susceptibility mapping (QSM), a novel MRI technology for solving the ill-posed phase-susceptibility equation to derive the voxel-wise magnetic susceptibility (de Rochefort et al., 2010; Kressler et al., 2010; Li et al., 2011; Liu et al., 2009, 2011b; Schweser et al., 2011b; Shmueli et al., 2009; Wharton et al., 2010; Wu et al., 2012). To date, QSM has been applied in studying cerebral micro-bleeds (Liu et al., 2012b), differentiating iron deposits from calcifications (Deistung et al., 2013), quantifying iron overload in Parkinson's diseases (Lotfipour et al., 2012), assessing the abnormalities in white matter myelination (Liu et al., 2011a), and in many other applications (Duyn, 2013; Reichenbach, 2012).

QSM attempts to solve an ill-posed inverse problem, and many methods have been developed to stabilize the inversion. While threshold-based k-space division or multi-orientation methods have been used in earlier studies (Liu et al., 2009; Shmueli et al., 2009), iterative solutions with regularization and prior information from magnitude or phase are increasingly used for single-orientation reconstruction with reduced streaking artifacts (de Rochefort et al., 2010; Liu et al., 2011b). Although prior information is highly useful in suppressing streaking artifacts around strong susceptibility sources, e.g. cerebral hematoma or large veins, one general concern is that excessive external constraints may alter the spatial frequencies of magnetic susceptibility in an unpredictable manner with degradation of tissue

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contrast. This is especially problematic for evaluating white matter lesions, whose susceptibility variations are small compared to that of major brain gray and white matter structures. Similar concerns also exist for studying small gray matter structures in the human brain, e.g. subthalamic nucleus, substantia nigra, cerebellar nuclei, which are small in size but have vital functions. Hence, eliminating streaking artifacts while minimizing the regularization-related confounding factors is crucial for evaluating subtle contrast changes in white matter diseases and for delineation of small but functionally important brain structures.

Previously, several methods have been proposed to separate the k-space into different sub-regions and to apply constraints only on ill-posed and ill-conditioned sub-regions (Li et al., 2011; Schweser et al., 2012; Wu et al., 2012). The results suggest that optimization of the ill-conditioned k-space region alone can reduce streaking artifacts. In this study, we propose a general method for estimating streaking artifacts and subtracting them from susceptibility maps. We demonstrate the application of the methodology in reducing streaking artifacts for the LSQR algorithm (Li et al., 2011). We show that, by estimating and subtracting out the streaking artifacts, reproducible QSM can be achieved with negligible streaking artifacts. This method allows for improved delineation of white matter lesions in multiple sclerosis patients and small brain structures in healthy human brains that otherwise would have been obscured by streaking artifacts. The proposed methodology can be extended to other existing QSM algorithms.

## Materials and methods

### *A method for estimating streaking artifacts*

The normalized phase ($\psi = \varphi/\gamma\mu_0 H_0 TE$) and magnetic susceptibility ($\chi$) can be related using the following equation (Koch et al., 2006; Marques and Bowtell, 2005; Salomir et al., 2003):

$$\psi = FT^{-1}\{D_2 \cdot FT(\chi)\} \tag{1}$$

where $\gamma$, $\mu_0$, $H_0$, and $TE$, are the gyromagnetic ratio, vacuum permeability, applied magnetic field, and echo time, respectively; $FT$ means Fourier transform; and $D_2$ can be calculated from the spatial frequency ($\mathbf{k}$) and the field direction $\hat{\mathbf{H}}$ as:

$$D_2 = \frac{1}{3} - \left(\hat{\mathbf{H}} \cdot \mathbf{k}\right)^2 \left(k_x^2 + k_y^2 + k_z^2\right)^{-1}. \tag{2}$$

For a given initial susceptibility estimation ($\chi_0$) obtained by solving Eq. (1), the streaking artifacts can be assumed to have originated from inaccuracies of inversion at ill-conditioned k-space regions. As such, the susceptibility artifacts in the k-space, $\chi_{SA}(k)$, can be estimated using the following minimization using the LSQR solver in Matlab:

$$\min_{\chi_{SA}(k)} \sum_i \left\| W_{Gi} \cdot G_i \left\{ \chi_0 - FT^{-1}[\chi_{SA}(k) \cdot M_{IC}] \right\} \right\|_2 \tag{3}$$

where $i = x, y$ and $z$; $G_i$ are gradient operators; $W_{Gi}$ are corresponding weights, which can be determined according to the estimated susceptibility boundaries and are defined in later sections; $M_{IC}$ is a binary mask of the ill-conditioned k-space regions:

$$M_{IC} = |D_2(k)| < D_{2,thres} \tag{4}$$

where $D_{2,\mathrm{thres}}$ is the threshold for $M_{IC}$ calculation.

The final susceptibility is obtained by subtracting the susceptibility artifacts from the initial susceptibility estimated by the LSQR method ($\chi_{LSQR}$):

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

For simplicity, the full method is referred to as the "iLSQR" method.

### *Initial susceptibility estimation using LSQR*

The LSQR method has been described previously (Li et al., 2011), which solves the following equation:

$$FT^{-1}\{D_2 \cdot FT(W_I \cdot \psi)\} = FT^{-1}\left\{D_2 \cdot FT\left[W_I \cdot FT^{-1}\{D_2 \cdot FT(\chi_{LSQR})\}\right]\right\}. \tag{6}$$

In this study, an image-space weighting term ($W_I$) is added to reduce artifacts arising from the inaccurate phase unwrapping around strong magnetic susceptibility sources. In this equation, the ill-conditioned phase-susceptibility relationship is weighted by another $D_2$ term in k-space for preconditioning. Since tissue interfaces with sharp phase changes are more prone to errors, $W_I$ is determined using the Laplacian of the phase data ($\nabla^2\varphi$) as:

$$\begin{cases} W_I = 1, \ \nabla^2\varphi < \nabla^2\varphi_{\min} \\ W_I = \left(\nabla^2\varphi_{\max} - \nabla^2\varphi\right) / \left(\nabla^2\varphi_{\max} - \nabla^2\varphi_{\min}\right), \ \nabla^2\varphi_{\min} \le \nabla^2\varphi \le \nabla^2\varphi_{\max} \\ W_I = 0, \ \nabla^2\varphi_{\max} < \nabla^2\varphi. \end{cases} \tag{7}$$

Here $\nabla^2\varphi_{\min}$ and $\nabla^2\varphi_{\max}$ are the thresholds used for calculating $W_I$, which can be adjusted to deal with different levels of phase unwrapping errors. Eq. (6) can be solved iteratively using the LSQR (Paige and Saunders, 1982) solver in Matlab. This LSQR allows for fast reconstruction of magnetic susceptibility with reasonable suppression of streaking artifacts, and provides an excellent initial estimation of susceptibility.

### *Susceptibility boundary estimation with fast QSM*

Streaking artifact estimation requires an estimation of the susceptibility boundaries for determining the weighting terms. Previously, Wharton and Bowtell (2010) showed that inaccurate boundary constraints will lead to distorted structures in the final susceptibility maps (Wharton and Bowtell, 2010). It is well known that the boundaries of magnitude and phase do not necessarily match that of susceptibility. As a result, they will lead to inaccurate susceptibility maps if used to generate the weighting masks. To address this problem, we developed a method for fast estimation of susceptibility contrast (referred to as the "fast QSM" method) with minimal streaking artifacts. This method provides a more accurate contrast for generating the weighting masks ($W_{Gi}$) compared to magnitude and phase.

The first step of this fast QSM method is to calculate an estimate of susceptibility contrast (in k-space) based on the positive or negative sign of $D_2$:

$$\chi_{F1}(k) = sign(D_2) \cdot FT(\psi). \tag{8}$$

A discontinuity in $\chi_{F1}(k)$ across the conical surface (defined by $D_2 = 0$) is expected, which is a significant source of streaking artifacts after Fourier transform. To attenuate this discontinuity, the discontinuous k-space data is averaged along the conical surfaces and inverse Fourier transformed into the image space:

$$\chi_{F2} = FT^{-1}\{\chi_{F1}(k) \cdot W_{FS} + Filter[\chi_{F1}(k)] \cdot (1 - W_{FS})\} \tag{9}$$

where *Filter* represents a low-pass filtering operation to remove the discontinuity. In this study, a spherical mean value filter is used with a small radius of 2–3 mm to ensure the locality of the k-space data,