Improving estimation of small-vein susceptibility by using a pre-estimated susceptibility map

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Target Audience: Researchers and clinicians working with or interested in quantitative susceptibility mapping (QSM).

Introduction:

QSM is expected to be applied to early diagnosis of neurodegenerative or cerebrovascular diseases. Several approaches for QSM have been proposed.[1,2] Of these, the method using structural information from a magnitude image as additional information[1] can estimate susceptibility with high accuracy, especially in tissues where contrasts between magnitude images and susceptibility distributions are consistent, such as deep gray-matter nuclei. However, susceptibility of small veins is often underestimated because of inconsistency between contrasts of small veins in a magnitude image and those in a susceptibility distribution. In this research, to reduce underestimation of small-vein susceptibility, a method is proposed for QSM; namely, instead of a magnitude image, a pre-estimated susceptibility map is used as structural information. The pre-estimated susceptibility map is calculated without regularization in order to preserve small-vein contrasts. In addition, to improve susceptibility of sub-voxel veins, the values in the high-frequency domain in k-space is replaced by the pre-estimated susceptibility map. The effects of using the pre-estimated susceptibility map as structural information and high-frequency values on susceptibilities of small veins were evaluated in experiment using healthy volunteer.

Methods:

Proposed method A schematic view of k-space used in the proposed method is shown in Fig. 1. As for the proposed method, k-space is divided into low- and high-frequency domains. In the low-frequency domain, L1-regularization using an unregularized susceptibility map as structural information is performed to suppress streaking artifacts and preserve susceptibility of deep gray-matter nuclei and small veins. In the L1-regularization, the low-frequency domain is further divided into magic-angle and non-magic-angle domains in order to apply regularization focused on an ill-conditioned domain as previously reported[3]. In the high-frequency domain, the unregularized susceptibility map is used to reduce underestimation of sub-voxel veins. The processing flow of the proposed method is shown in Fig. 2. First, susceptibility maps $\boldsymbol{\chi}_l$ and $\boldsymbol{\chi}_s$ are calculated by using an unregularized weighted least-squares algorithm[4] with two different iteration numbers, n_l and n_s ($n_l > n_s$), respectively. Second, susceptibility map $\boldsymbol{\chi}'$ is calculated by smoothing the magic-angle domain of $\boldsymbol{\chi}_l$ by using L1-norm regularization and edge information of $\boldsymbol{\chi}_s$ according to the following equation: $\boldsymbol{\chi}' = \mathrm{argmin}_{\boldsymbol{\chi}'} \|\mathbf{M}_{\mathrm{nMA}}\mathbf{F}(\boldsymbol{\chi}'-\boldsymbol{\chi}_l)\|_2^2 + \lambda(\|\mathbf{M}_x\mathbf{G}_x\boldsymbol{\chi}'\|_1+\|\mathbf{M}_y\mathbf{G}_y\boldsymbol{\chi}'\|_1+\|\mathbf{M}_z\mathbf{G}_z\boldsymbol{\chi}'\|_1)$, where $\mathbf{M}_{\mathrm{nMA}}$ denotes weight in k-space, $\mathbf{F}$ denotes a 3D Fourier-transform operator, λ denotes a regularization parameter, $\mathbf{M}_x$, $\mathbf{M}_y$, and $\mathbf{M}_z$ denote binary edge masks in the x, y, and z directions, respectively, and $\mathbf{G}_x$, $\mathbf{G}_y$, and $\mathbf{G}_z$ denote gradient operators in the x, y, and z directions, respectively. $\mathbf{M}_{\mathrm{nMA}}$ is calculated by using threshold m_{th} and a hyperbolic function as $\mathbf{M}_{\mathrm{nMA}} = [1+\tanh\{m_{cur}\cdot(|1/3 - k_z^2/k^2)| - m_{th})\}]/2$, where $k^2=k_x^2+k_y^2+k_z^2$ and m_{cur} is a constant. $\mathbf{M}_x$ is defined as 1 where $|\mathbf{G}_x\boldsymbol{\chi}_s| < \alpha_s$ and 0 otherwise where α_s is a constant, and $\mathbf{M}_y$ and $\mathbf{M}_z$ are defined in the same manner as $\mathbf{M}_x$. Lastly, susceptibility map $\boldsymbol{\chi}$ is calculated by replacing values in the high-frequency domain of $\boldsymbol{\chi}'$ by those of $\boldsymbol{\chi}_s$ according to the following equation: $\boldsymbol{\chi} = \mathbf{F}^{-1}\{(\mathbf{1}-\mathbf{M}_H)\mathbf{F}\boldsymbol{\chi}' + \mathbf{M}_H\mathbf{F}\boldsymbol{\chi}_s\}$, where $\mathbf{M}_H$ denotes weight in k-space and is calculated using threshold k_{th} and a hyperbolic function as $\mathbf{M}_H = [1+\tanh\{k_{cur}\cdot(|k| - k_{th})\}]/2$, where k_{cur} is a constant. *Experiment* Healthy volunteer was scanned in a 3T MRI (TRILLIUM OVAL, Hitachi Medical Corporation, Japan). The main scan parameters in axial slices are listed as follows: sequence: 3D RSSG (RF-spoiled-Steady-state Acquisition with Rewound Gradient Echo)-EPI; TR/TE = 40/20 ms; NSA = 2; FA = 20; ETL = 5; matrix: 512×384×40; reconstruction matrix: 512×512×64; and FOV: 220×220×80 mm. *Susceptibility calculation* Three susceptibility maps, $\boldsymbol{\chi}_M'$, $\boldsymbol{\chi}'$, and $\boldsymbol{\chi}$, were calculated. In the calculation, $\boldsymbol{\chi}_M'$ was calculated in the same manner as $\boldsymbol{\chi}'$, except that edge information of a magnitude image was used instead of $\boldsymbol{\chi}_s$. The main calculation parameters are listed as follows: $n_l = 50$, $n_s = 3$, $m_{th} = 0.1$, and $k_{th} = 0.6$. The value of λ was selected using the L-curve. *Evaluation* To evaluate the effects of using a pre-estimated susceptibility map as structural information, small-vein susceptibilities of $\boldsymbol{\chi}_M'$ and $\boldsymbol{\chi}'$ were compared. To evaluate the effects of using a pre-estimated susceptibility map as high-frequency values in k-space, small-vein susceptibilities of $\boldsymbol{\chi}'$ and $\boldsymbol{\chi}$ were compared.

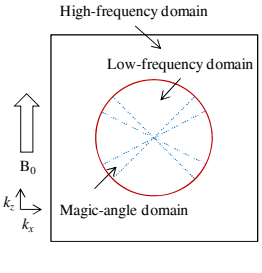
Results and discussion:

The contrasts of small veins in $\boldsymbol{\chi}'$ are improved compared to those in $\boldsymbol{\chi}_M'$ (white arrows in Figs. 3b and 3c), and susceptibilities of veins in $\boldsymbol{\chi}'$ are larger than those in $\boldsymbol{\chi}_M'$ (Fig. 4a). These results suggest the underestimation of small-vein susceptibility is reduced by using a pre-estimated susceptibility map, instead of a magnitude image, as structural information. The contrasts of sub-voxel veins in $\boldsymbol{\chi}$ are improved compared to those in $\boldsymbol{\chi}'$ (red arrows in Figs. 3c and 3d), and the susceptibilities of veins in $\boldsymbol{\chi}$ are larger than those in $\boldsymbol{\chi}'$ (Fig. 4b). These results suggest that underestimation of the susceptibility of sub-voxel veins is reduced by using a pre-estimated susceptibility map as high-frequency values in k-space.

Conclusion:

Underestimation of small-vein susceptibilities is reduced by using a pre-estimated susceptibility map as structural information and high-frequency values in k-space.

References: 1. Liu T, et al., MRM 2011;66:777-783, 2. Shmueli K, et al., MRM 2009;62:1510-1522, 3. Wu B, et al. MRM 2012;67:137-147, 4. Sato R, et al., ISMRM2014;3186



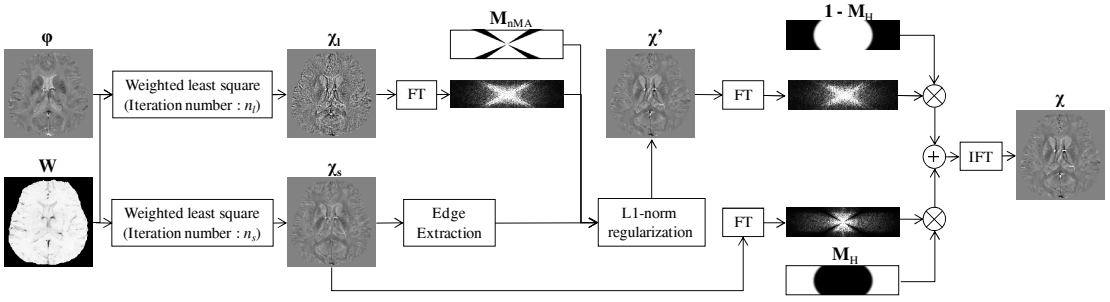


Figure 1(left). Schematic view of k-space used in the proposed method. **Figure 2(right)**. Processing flow of the proposed method.

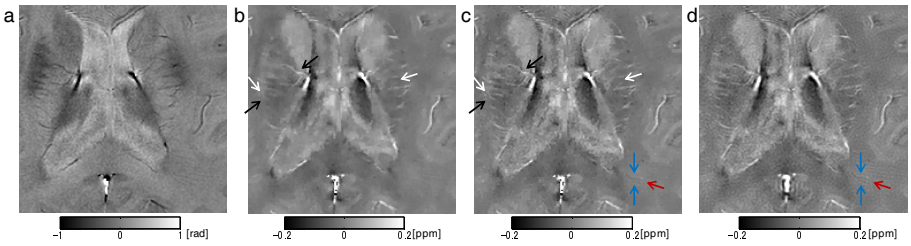


Figure 3. Enlarged images of phase image and susceptibility maps: (a) phase image, (b) susceptibility map $\boldsymbol{\chi}_M'$, (c) susceptibility map $\boldsymbol{\chi}'$, and (d) susceptibility map $\boldsymbol{\chi}$.

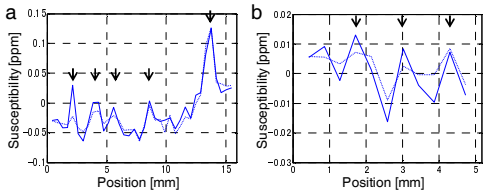


Figure 4. Line profiles of veins susceptibilities (a) indicated by black arrows in Fig. 3b (dotted line) and Fig. 3c (solid line) and (b) indicated by blue arrows in Fig. 3c (dotted line) and Fig. 3d (solid line). Arrows indicate position of veins.