Quantitative Susceptibility Mapping Using Adaptive Edge-Preserving Filtering

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Introduction

Quantitative susceptibility mapping (QSM) is very useful for obtaining biological information such as iron content or blood oxygen saturation. Several QSM methods have been proposed to solve the magnetic field to susceptibility source inverse problem. Most general methods are regularization approaches, including morphology enabled dipole inversion (MEDI) [1-3]. Although these approaches can reduce noise and artifacts with regularization terms, the quality of the susceptibility value depends on the regularization parameter λ. Improper choices result either in over-smoothing with concomitant loss of subtle susceptibility contrast or in streaking artifacts [4]. In this paper, we propose a novel QSM reconstruction method that reduces artifacts and generates a high quantitative susceptibility map without the regularization terms. The method combines an iterative least square technique with an adaptive edge-preserving filtering. We demonstrate the results of a numerical phantom simulation and a healthy volunteer experiment utilizing the proposed method.

Method

Algorithm Figure 1 shows a flowchart of the proposed QSM reconstruction method. The method consists of three steps: (I) iterative least square minimization [steps (a) - (e)], (II) adaptive edge-preserving filtering to the susceptibility map in the minimization process [step (f)], and (III) weighted addition of the susceptibility map in k-space before and after filtering [steps (g) - (i)]. The cost function in the iterative least square minimization is defined by the equation $e(\chi_i) = \| W(C\chi_i - \delta) \|_2^2$, where C denotes a matrix representing the convolution with the dipole kernel, δ denotes the measured local field, and W denotes the weighting matrix. In step (f), the adaptive edge-preserving filter is defined by the equation $\chi_i(r) = \mu(r) + (\sigma(r)^2 - \nu^2)(\chi_i(r) - \mu(r))/\sigma(r)^2$, where r denotes the coordinates of a voxel, μ and σ^2 denote the average and variance of the local window, (i.e. 3 × 3), in the susceptibility map, respectively. ν^2 is a parameter corresponding to the noise variance of the whole susceptibility map. In step (h) of the weighted addition of the susceptibility map in k-space, the weighting matrices G and G_k are defined by the equations $G(k) = 1$, (if $|D(k)| \geq a_{th}$), $G(k) = D(k)/a_{th}$, (if $|D(k)| < a_{th}$), $G_k(k) = 1 - G(k)$, where k denotes the coordinates in k-space, a_{th} denotes the boundary threshold of a magic angle in k-space, and $D(k)$ denotes a dipole kernel expressed in k-space ($D(k) = 1/3 - k_z^2/(k_x^2 + k_y^2 + k_z^2)$).

Numerical simulation As shown in Fig. 2, a 3D numerical phantom was generated to evaluate the accuracy of the proposed method. A phase map was computed by using the convolution of the susceptibility map and dipole kernel. A complex MR image, which was added with complex Gaussian noise corresponding to the desired SNR (= 40), was calculated by using the magnitude and phase map. The optimality of QSM was defined by the relative error $\|\chi_e - \chi_m\|^2/\|\chi_m\|^2$ of the estimated susceptibility map χ_e with respect to the model susceptibility map χ_m. To assess accuracy, a linear regression was performed between the estimated susceptibilities and the model values.

Human study A healthy volunteer experiment was performed on a 3T MR imaging scanner (TRILLIUM OVAL, Hitachi Medical Corporation, Japan). The main parameters in the axial slices were sequence: 3D RSSG (RF-spoiled-Steady-state Acquisition with Rewound Gradient-Echo)-EPI, TR/TE = 40/20 ms, FA = 20°, NSA = 2, ETL = 5, FOV: 220 × 220 × 80 mm, and matrix: 512×384×40 (zero filled to 512 × 512 × 64).

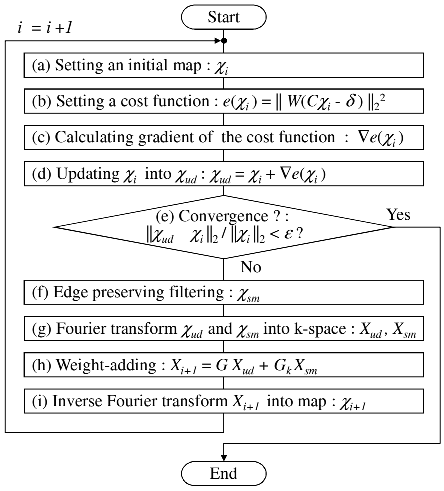

Fig. 1: Flowchart of the proposed reconstruction

Results and Discussion

Figures 3 show the results of the numerical simulations for MEDI and the proposed method. The optimal choices of λ (= $10^{-2.9}$) or a_{th} (= 1.0), as shown by the black arrow, are selected from the minimal relative error of each method. As shown in Figs. 3(d)(h), the slope of the linear regression of MEDI fell short of 1.0. In comparison, that of the proposed method come up to 1.0 when the a_{th} was more than 0.5. As shown in Fig. 4, the proposed method could suppress the noise and artifacts. Moreover, the microstructure of the susceptibility map was visible with the proposed method as well as with MEDI. This is reason that the edge preserving filtering of the proposed method has the specific characteristic described below. In the region where local variance is small, since this filter performs strong smoothing, a value approaches to the local average value. Therefore, the noise and artifacts are suppressed and quantification of the susceptibility is maintained. Additionally, in the region where local variance is large, the filter performs weak smoothing. Therefore the microstructure of the susceptibility map is preserved.

Conclusion

We proposed a novel QSM reconstruction method that combines an iterative least square technique with adaptive edge-preserving filtering. The results from numerical simulation and a human experiment showed that this method reduces the artifacts and generates a high-quality susceptibility map.

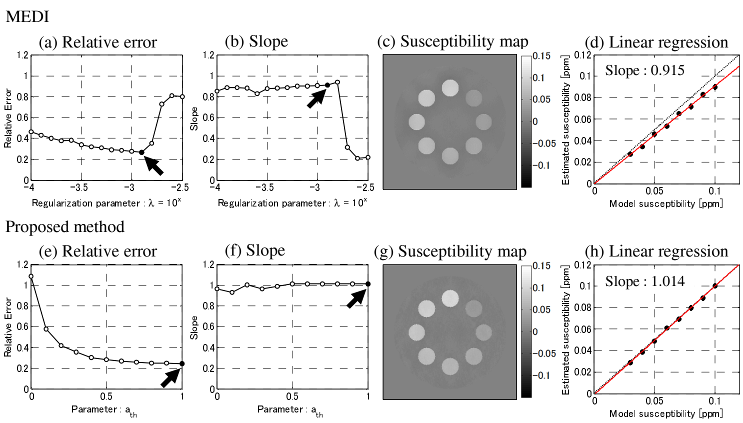

Fig. 3: Results of numerical simulation of MEDI(upper) and proposed method (lower). Left to right graphs or images are shown as relative error, slope, reconstructed susceptibility map, and linear regression between model susceptibility and estimated susceptibility, respectively.

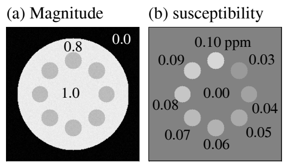

Fig. 2: 3D numerical phantom for simulation (coronal plane). (a) magnitude image, and (b) susceptibility map

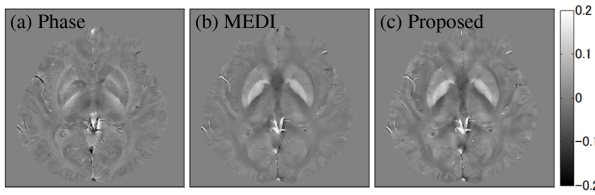

Fig. 4: Results of a healthy volunteer of (a) phase image, (b) a susceptibility map estimated by MEDI (λ=$10^{-3.5}$), and (c) the proposed method (a_{th}=0.6).

References

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