Quantitative Susceptibility Mapping Reconstruction with Spatial Prior: Shortening Reconstruction Time and Choosing Regularization Parameters Automatically

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Purpose: Quantitative susceptibility mapping (QSM) provides a way to quantify bulk magnetic susceptibility distribution from field inhomogeneity images. It involves phase unwrapping, background filtering and source reconstruction. QSM reconstruction with spatial priors [1] can be performed to solve this ill-posed problem. However, the iterative procedure is limited by a long calculation time, and multiple iterations are needed to choose adequate regularization parameters. Here we accelerate QSM using a rapid estimation in *k*-space and introduce a general and efficient parameter search method.

Methods: Phase unwrapping and background filtering were first performed with an optimized version of an algorithm based on harmonic filtering [2] which was here solved directly in frequency domain using an integral filter design approach. To reconstruct susceptibility from the normalized internal field B_{in}/B_0, the regularized approach with weighted gradients (W_GG) consisting in minimizing the norm $\left\| W(C\chi - B_{in}/B_0) \right\|_2^2 + \lambda^2 \left\| W_G G\chi \right\|_2^2$ [1] was optimized in the regularization parameter λ choice following two approaches. The automatic residual noise approach was first accelerated using a Newton's method [3] to obtain a coarse estimate. The residual noise can be evaluated by $\left\| W(C\chi_{opt} - B_{in}/B_0) \right\|^2 = N/(\gamma B_0 TE)^2$, with total voxel number N within region of interest. After determining a small interval for λ, an automatic estimation of homogeneity in *k*-space was performed for fine tuning. This approach was done by comparing the standard deviations (SD) in *k*-space (Fig.1) for regions including and excluding the magic angle (55°). This ratio is expected to be <1 for over-regularized solutions, >1 for under-regularized solutions and close to 1 if noise and signal power are similar.

These approaches were applied on a simulated dataset (as in [1]) and on *ex vivo* Alzheimer's disease mouse model brain injected with Ultra Small Particles of Iron Oxide (USPIO) [4]. *Ex vivo* imaging was performed at 2.35T (BioSpec) with a 3D gradient-echo (GRE) sequence: 10/75ms TE/TR, 17° flip angle, 78×80×100µm resolution and 256×128×256 matrix size. Susceptibility was converted to iron concentration assuming a molar susceptibility of 2300ppmL/mol at 2.35T [5].

Results: For the simulated data (matrix size 192^3), convergence was obtained in less than 3 min for each iteration. The optimized parameter was automatically chosen in less than 15 min. The fitted susceptibility as a function of the input value shows a slope close to 1 which indicates accurate reconstruction (Fig.2e). The magnetic sources produced by USPIO deposition were reconstructed efficiently around 20 min (2.5 min for each iteration) by each optimization approach (Fig.3). Iron map (Fig.3d) showed USPIO focal accumulations having susceptibility values up to 2.8ppm (1.2mmol/L) while background noise SD was estimated to be 0.02ppm (8.7µmol/L). QSM provided efficiently additional quantitative information to traditional GRE amplitude and phase images.

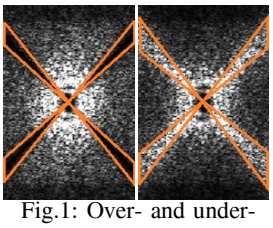

Fig.1: Over- and under-regularized *k*-space of *ex vivo* data with the ROI drawn around 55°.

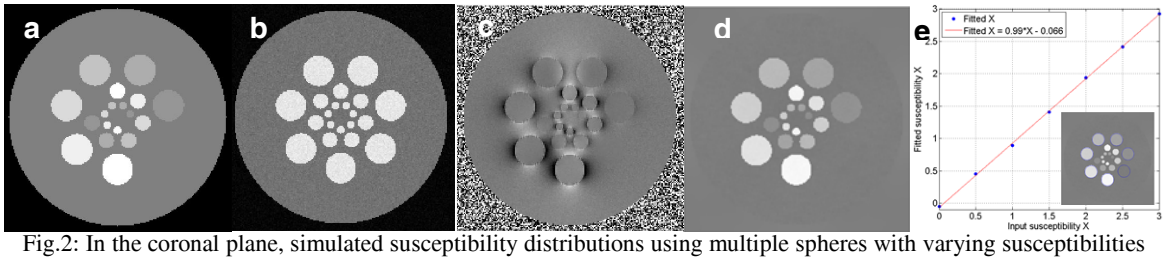

Fig.2: In the coronal plane, simulated susceptibility distributions using multiple spheres with varying susceptibilities and diameters (a), associated MR signal magnitude (b), simulated field (c), optimized susceptibility reconstruction (d) and quantitative validation of reconstructed maps (e).

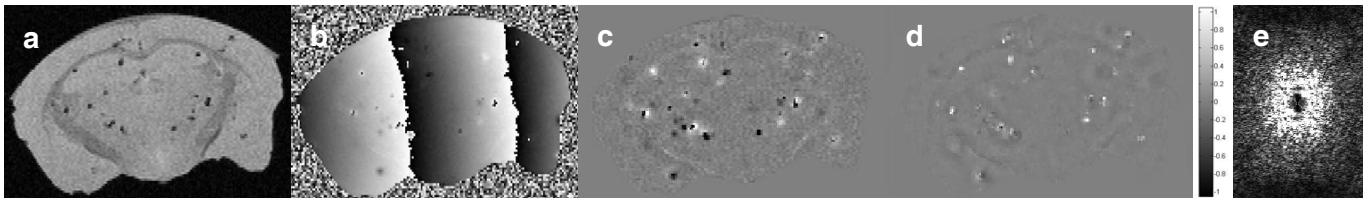

Fig.3: Signal intensity (a) and phase (b) maps in a selected coronal slice in an Alzheimer mouse. Internal field was obtained by the harmonic filtering (c) displaying USPIO accumulation. Iron map (d) issued from QSM and optimal reconstructed *k*-space (e).

Discussion and Conclusion: The reconstruction time of QSM involving spatial priors can be reduced by a factor ~9 compared to the initial iterative algorithm. The proposed parameter search method is efficient to find an optimized regularization parameter. Additionally, we presented a general method evaluating variations in *k*-space that can be used to estimate the quality of other QSM reconstruction techniques. QSM was applied here to evaluate nanoparticle deposition in an animal model of Alzheimer's disease and can potentially find pre-clinical and clinical applications in molecular MRI studies.

References: **1.** de Rochefort *et al.*, MRM 2010. **2.** de Rochefort *et al.*, ISMRM 2010. **3.** Tjalling *et al.*, SIAM 1995. **4.** Raynaud *et al.*, ISMRM 2010. **5.** de Rochefort *et al.*, MRM 2008.