

Quantitative susceptibility mapping with superfast dipole inversion: Influence of regularization parameters on the susceptibility of the substantia nigra and the red nucleus

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Target audience: MR physicists, Neuroscientists

Purpose: To analyze the influence of the choice of regularization parameters on the results of quantitative susceptibility mapping (QSM)^{1,2} using the superfast dipole inversion (SDI)³ technique.

Methods: QSM of the brain was performed in 11 healthy volunteers (age 57–68 years, 6 female) on a 3-Tesla whole-body MRI system (Magnetom Verio, Siemens Healthcare, Erlangen, Germany). 3D gradient-echo image data sets (magnitude and phase) with an isotropic spatial resolution of 1×1×1 mm³ were acquired (TR: 41 ms, TE: 10,20,30 ms, flip angle: 20°, matrix: 256×192×144). The superfast dipole inversion algorithm proposed by Schweser et al.³ was used to determine quantitative susceptibility maps of the brain: First, the discrete Laplacian of the unwrapped phase (TE=20 ms) was calculated from the wrapped phase images (using the Schofield and Zhu approach⁴) and multiplied with the brain-tissue mask (determined using the FSL brain extraction tool) resulting in ϕ_{ML} . Then, the Fourier transform of ϕ_{ML} , $FT(\phi_{ML})$, was multiplied by the SDI kernel $K(\delta, \sigma; \tau; \mathbf{k}) = L^{-1}(\sigma; \mathbf{k}) \cdot \tau^{-1} \cdot d^{-1}(\delta; \mathbf{k}) \cdot c_{\chi}^{-1}(\delta)$ consisting of the inverse Laplace operator, $L^{-1}(\sigma; \mathbf{k})$, the inverse unit dipole, $d^{-1}(\delta; \mathbf{k})$, a correction for dipole inversion effects, $c_{\chi}^{-1}(\delta)$, and the acquisition-parameter term $\tau = \gamma TE B_0$. The susceptibility map, χ , was obtained as the inverse Fourier transform of this product, i.e. as $\chi = FT^{-1}[FT(\phi_{ML}) \cdot K(\delta, \sigma; \tau; \mathbf{k})]$.

The influence of the parameters σ (regularization of Laplace operator inversion) and δ (regularization of unit dipole inversion) was analyzed for $\sigma = \{0.05, 0.10, 0.15, 0.20\}$, $\delta = \{0.20, 0.33, 0.50, 0.66\}$ and evaluating all 16 combinations of these parameters. Target parameters were the relative susceptibilities (after subtraction of the CSF susceptibility value) in the substantia nigra (SN) and in the red nucleus (RN). Both 3D regions were defined using manual segmentations in a normalized group atlas created with a registration toolbox (Greedy SyN, ANTs, Avants et al.⁵). The atlas labels were then propagated to individual subject MRIs using the deformation fields. Dice overlap coefficients with single-subject manual segmentations were calculated in a single medial slice for SN/RN as 0.76/0.76.

Reference evaluations were performed using the single-angle acquisition (SAA) QSM framework described by Schweser et al.² based on the iterative solution of the linear system of equations $\mathbf{A} \chi = \delta_{int}$, where multiplication with the matrix \mathbf{A} represents the dipole response and δ_{int} is the internal magnetic field perturbation. This linear system of equations was solved with a Krylov-subspace solver (regularization: $\beta=0.08$).

Results: For the substantia nigra, the reference evaluation resulted in susceptibilities (average over the target region) between 0.058 and 0.099 ppm in the 11 subjects, the mean value over all subjects was 0.077 ppm (std. dev. 0.013 ppm). For the red nucleus, values between 0.046 and 0.090 ppm were found with a mean value of 0.068 (0.014) ppm (Fig. 1). The SDI evaluations showed a large variability depending on σ and δ (Fig. 2). For small regularization parameters, the susceptibilities increased substantially to mean values up to about 0.20 ppm. Results close to the reference results were obtained for $\sigma \approx 0.15$ and $\delta \approx 0.5$.

Discussion: According to our results, the choice of the regularization parameters substantially influences the determined tissue susceptibilities with variations much greater than the interindividual variations in the evaluated target regions. Fortunately, the parameters $\sigma \approx 0.15$ and $\delta \approx 0.5$ lie in a “flat” part of the parameter space where the variation of the susceptibility is relatively low, i.e. the results remain robust for small variations of σ and δ . Comparing our results with previously published values, the susceptibilities of the red nucleus are comparable (although slightly lower) with those given by Schweser et al.², while our results for the substantia nigra are substantially lower. This may be explained by the size and extent of the evaluated 3D ROIs, which were segmented automatically in this study and may be larger than in previous studies.

Conclusions: Our results demonstrate that one should be aware of the influence of the regularization parameters on the quantitative results of QSM with the SDI approach. $\sigma \approx 0.15$ and $\delta \approx 0.5$ lead to results compatible with the slower (iterative) SAA QSM approach used as reference in this study.

References: 1. Liu T et al. Magn Reson Imaging. 2010;28:1383, 2. Schweser F et al. Neuroimage. 2011;54:2789, 3. Schweser F et al. Magn Reson Med 2013;69:1582, 4. Schofield MA et al. Opt Lett. 2003;28:1194, 5. Avants BB et al. Neuroimage. 2011;54:2033

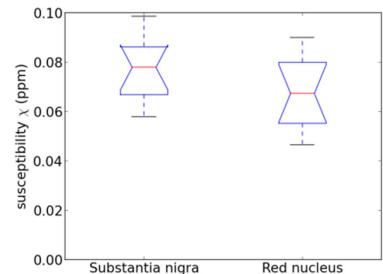


Fig. 1: Susceptibilities of the substantia nigra and the red nucleus (reference evaluation over 11 subjects).

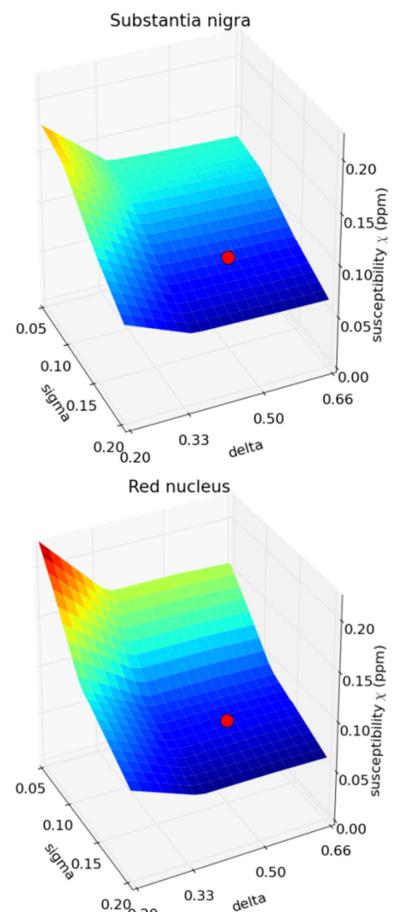


Fig. 2: SDI susceptibilities of the substantia nigra (top) and the red nucleus (bottom) averaged over all 11 subjects as function of the regularization parameters. The red dot indicates regularization parameters $\sigma \approx 0.15$ and $\delta \approx 0.5$ which give results compatible with the iterative non-SDI evaluation.