Single-Step Quantitative Susceptibility Mapping using Total Generalized Variation and 3D EPI

Kristian Bredies[1], Stefan Ropele[2], Benedikt A Poser[3], Markus Barth[4], and Christian Langkammer[2]

[1]*Institute of Mathematics and Scientific Computing, University of Graz, Graz, Austria,* [2]*Department of Neurology, Medical University of Graz, Graz, Austria,* [3]*Faculty of Psychology and Neuroscience, Maastricht University, Maastricht, Netherlands,* [4]*Donders Institute for Brain, Cognition and Behaviour, Radboud University Nijmegen, Nijmegen, Netherlands*

Target audience: Researchers interested in susceptibility mapping and reconstruction, anatomical imaging, phase imaging, and iron deposition.

Purpose: Quantitative susceptibility mapping (QSM) has recently gained increased interest as it has shown excellent white-gray matter contrast and the ability to assess a fundamental physical property in-vivo. Dipole inversion methods using the total-variation (TV) functional have been proposed as approaches to reconstruct the distribution of magnetic susceptibility from gradient echo phase data after unwrapping and background field removal [1-3]. However, TV only takes the first derivative into account and is unaware of higher-order smoothness which produces so-called staircase artifacts for images that are not piecewise constant. The generalized TV (TGV) functional [4] shares convenient properties of the TV functional, but is also able to deal with higher-order smoothness and therefore leads to more natural solutions as exemplarily shown in Figure 1. Moreover, as the reconstruction usually involves multiple steps, errors might propagate in each step. In this work, we propose a new and robust TGV-based QSM reconstruction which reconstructs susceptibility maps in a single integrative step. This novel approach was applied to gradient echo phase data which was rapidly acquired with a three dimensional EPI sequence.

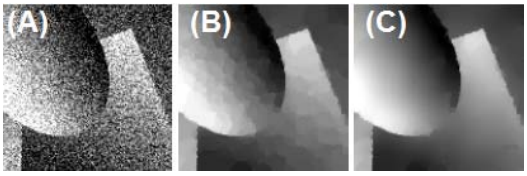

Figure 1: Noisy image (A) and results of TV- (B) and TGV-based variational denoising (C).

Methods*: MR imaging:* Three subjects (age range: 24-31 years) underwent MRI at 3T (TimTrio, Siemens Healthcare) including a 3D gradient echo EPI sequence [5] with 1mm isotropic resolution (TR/TE=90/27ms, FOV=230x230x176). Images were acquired using a 32 channel phased array with a parallel imaging factor of 3x1. Images were acquired with 1, 4 and 8 averages yielding total acquisition times including the time for the pre-scans (TA) of 29s, 1:05min and 1:59min, respectively.

QSM reconstruction: QSM maps were recovered from the wrapped phase of single gradient echo data ϕ_{wrap} by an optimization procedure based on the relation $\Delta\phi = \Im((\Delta\exp(j\phi_{wrap}))\exp(-j\phi_{wrap}))$ for the Laplacian of unwrapped phase ϕ [6] as well as by inverting $\frac{1}{3}\frac{\partial^2\chi}{\partial x^2}+\frac{1}{3}\frac{\partial^2\chi}{\partial y^2}-\frac{2}{3}\frac{\partial^2\chi}{\partial z^2}=\frac{1}{2\pi T_E\gamma B_0}\Delta\phi$ for the susceptibility χ. The background field was incorporated by an auxiliary variable ψ for which its Laplacian equals the discrepancy of the latter equation on the brain mask Ω. Additionally, the inversion was regularized with TGV of second order and parameters $\alpha=(\alpha_0,\alpha_1)$ resulting in the variational problem:

$\min_{\chi,\psi}\int|\psi|^2dx+TGV_\alpha^2(\chi)$ subject to $\Delta\psi=\frac{1}{3}\frac{\partial^2\chi}{\partial x^2}+\frac{1}{3}\frac{\partial^2\chi}{\partial y^2}-\frac{2}{3}\frac{\partial^2\chi}{\partial z^2}-\frac{1}{2\pi T_E\gamma B_0}\Delta\phi$ in Ω.

The TGV functional itself introduces one more auxiliary variable as $TGV_\alpha^2(\chi)=\min_w\alpha_1\|\nabla\chi-w\|_M+\alpha_0\|\varepsilon w\|_M$. The solution of this optimization problem yields susceptibility maps in a single step – without the need of separate phase unwrapping and background field fitting. It can be performed numerically by general primal-dual algorithms for finding saddle points for convex-concave problems. For the computations, the iterative method was implemented as described in [7] on a machine with two six-core AMD Opteron 2.2 GHz processors and 24 GB of RAM.

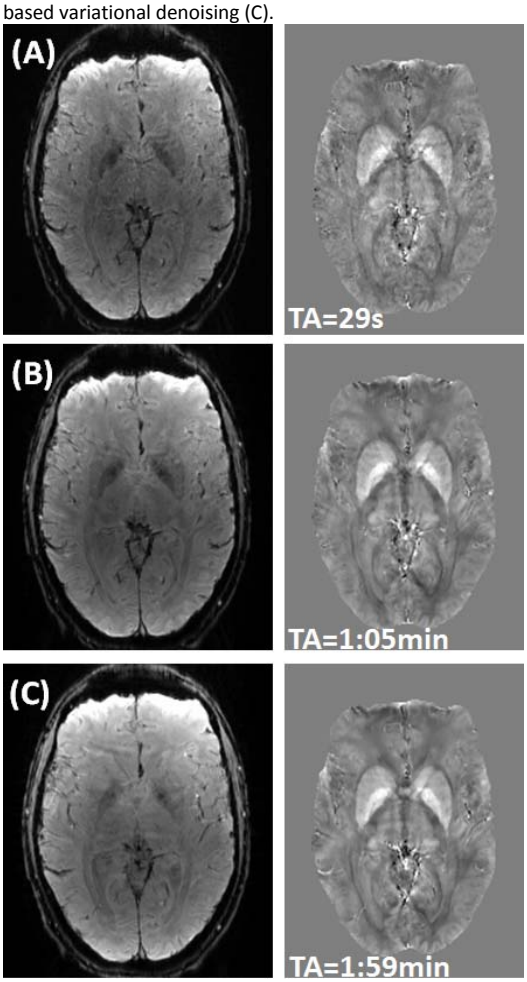

Figure 2: Magnitude and QSM images with 1 (A), 4 (B) and 8 averages (C). QSM images scaled from -0.25 to 0.25 ppm.

Results: TGV-based reconstruction yielded reliable QSM images even from low SNR phase images acquired in 29 seconds (Figure 1A). More signal averages resulted in a more stable reconstruction (Figures 1B and 1C). ROI analysis revealed substantially more variance in regional susceptibility for 1 average, while acquiring more than 4 averages did not substantially change quantitative measurements. Mean susceptibilities for basal ganglia regions with high iron levels are given in Table 1.

Region	1 Average	4 Averages	8 Averages
Putamen	0.068±0.029	0.077±0.019	0.081±0.016
Pallidus	0.188±0.045	0.202±0.041	0.195±0.036
Red Nucl	0.164±0.028	0.128±0.026	0.126±0.022

Table 1: Regional susceptibility grouped by number of averages (given as mean ± SD, in ppm).

Discussion and Conclusion: 3D EPI acquisition combined with single-step TGV reconstruction yielded reliably QSM images of the entire brain with 1mm isotropic resolution in 1 minute acquisition time. As add-on to a clinical imaging protocol, this offers the possibility to assess micro-bleeds, differentiate them from calcifications or quantify age related as well as disease induced iron deposition [8,9]. Additionally, as reconstruction is carried out in a single optimization step the proposed TGV-based reconstruction has algorithmic advantages such as robustness against low SNR data and provides high quality of the QSM maps because higher-order information is incorporated in the reconstruction procedure.

References: [1] Schweser F, Neuroimage, 2012, 62(3):2083, [2] Bilgic B, Neuroimage, 2012, 59(3):2625, [3] Liu T, Magn Res Med, 2011, 66(3):777, [4] Bredies K, SIAM Journal of Imaging Sciences, 2010, 3(3):492, [5] Poser BA, Neuroimage, 2010, 51(1):261, [6] Schofield M, Optics Letters, 2003, 28(14):1194-1196, [7] Chambolle A, Journal of Mathematical Imaging and Vision, 2011, 40(1):120-145, [8] Langkammer C, Radiology, 2013, 267(2):551, [9] Li W, Human Brain Mapp., 2013, Sept 13 (Epub)