Quantitative Susceptibility Mapping (QSM) at 7 Tesla:Correction of Induced Field Fluctuations with Real-Time Feedback Field Control

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Target Audience: Researchers interested in MRI, QSM, MR Signal Phase, 7T, Field Monitoring, Real-Time Feedback Field Control.

PURPOSE T2*-weighted imaging methods can strongly suffer from artifacts caused by spatiotemporal field fluctuations and corresponding variations of T2* decay rates, that cannot fully be corrected for by post-acquisition data processing methods. The field fluctuations can result from changes in the distribution of susceptible tissue due to respiration and limb motion. The effect scales with field strength and can severely degrade image quality at 7 Tesla[1]. A method has been introduced that minimizes such fluctuations by means of magnetic field monitoring with NMR field probes[2-4] and real-time full 3rd order field stabilization[5]. The method has been shown to effectively reduce breathing artifacts in T2*-weighted images and T2* maps acquired at 7T [5, 6]. In this study we present, for the first time, an assessment of the potential of real-time field control for enhancing the accuracy of quantitative susceptibility mapping (QSM) under common temporal field fluctuations.

MATERIALS AND METHODS All images were acquired on a 7T MR system (Achieva, Philips Healthcare, Best, The Netherlands).

Experiment: Complex-valued images of two consenting volunteers were acquired with the following parameters: 3D Multi-Gradient-Echo, TE_1 = 3ms, TR = 80, FA = 15, voxel size: 0.77 x 0.77 x 1.8 mm, Volunteer #1: 6TE, ΔTE=10ms, Volunteer #2: 8TE, ΔTE=8ms.

The sequence was repeated four times during 1 hour of study time. Subjects were instructed to breathe deeply during two scans (deep breathing: DB) and to move one arm to the chest and back several times during the other two (arm movement: AM). For both spatiotemporal field disturbance patterns a 3D data set was acquired once with and once without real-time feedback field control (FFC).

Data Processing: For all image series, multi-echo complex data were combined according to $WPI_w = angle\,(\frac{1}{N-1}\sum_{n=1}^{N-1} S_n^* S_{n+1})$ and then unwrapped and subject to background-field removal by the Laplacian-based SHARP (threshold parameter = 0.1) method using the relation: $L(WPI) = \cos(WPI_w)\,.\,L(\sin(WPI_w)) - sin(WPI_w).\,L(cos(WPI_w))$[7]. Background noise and convolution artifacts were reduced by element-wise multiplication with an eroded (3 voxels) binary whole-brain mask. Susceptibility difference maps were obtained from SHARP images by dipolar inversion, using the relation $\Delta X = FT^{-1}(\frac{FT(-SHARP/(\gamma B_0 \Delta TE))}{g})$, with the dipolar kernel $g = \frac{1}{3} - \frac{k_z^2}{k^2}$, $k^2 = \; k_x^2 + k_y^2 + k_z^2$, (FT = Fourier Transform, γ = magnetogyric ratio, B_0 = field strength, ΔTE = echo-time increment). Division by zero-values in g was avoided by thresholding and regularization [8, 9].

Difference Maps: QSM images acquired with and without real-time field control were realigned to each other using SPM8[10]. Difference maps were calculated as $\Delta QSM = QSM_{FFC}\text{-}QSM_{noFFC}$.

RESULTS Exemplary susceptibility maps for "*Deep Breathing*" and "*Arm Movement*" sessions (with and without FFC) for both volunteers are shown in Fig. 1 and Fig. 2, respectively. Some prominent differences between images acquired with versus without FFC are highlighted by arrows. Both Figures show the experiment without FFC, with FCC, and the corresponding difference map from left to right.

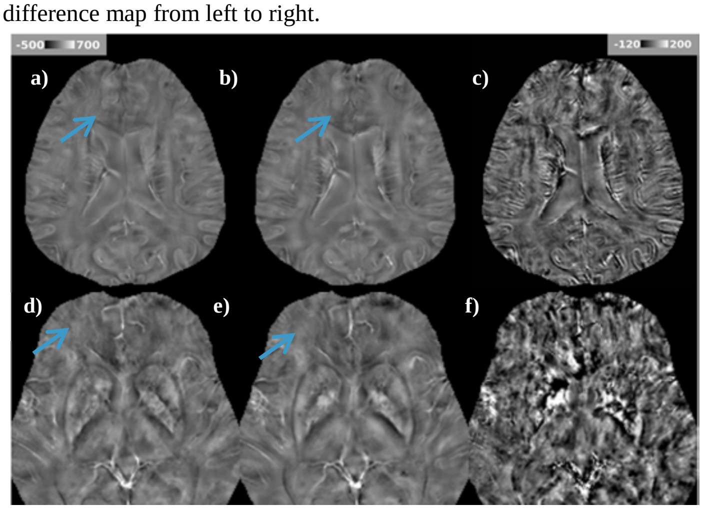

Fig.1: Volunteer #1, AM (a), AM/FFC (b), ΔQSM (b-a) (c), DB (d), DB/FFC (e), ΔQSM (e-d) (f)

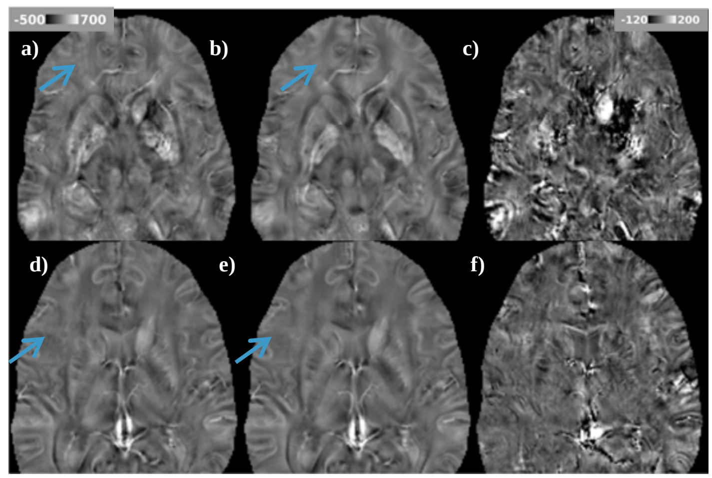

Fig.2: Volunteer #2, AM (a), AM/FFC (b), ΔQSM (b-a) (c), DB (d), DB/FFC (e), ΔQSM (e-d) (f)

DISCUSSION & CONCLUSION We demonstrated for the first time the impact of real-time high-order feedback field control on QSM. Field fluctuations induced by deep breathing and arm movement had less negative impact on image quality of susceptibility maps of the volunteers under active field-monitoring and control. Difference maps between with and without FFC (right columns) depict the main changes, which are the ghosting artifacts and edges of the structures, but also involve larger regions of altered signal intensity. These differences are mostly visible in frontal regions and grey matter structures (compare blue arrows). Utilization of field feedback resulted in better visibility and delineation of anatomical structures and their boundaries. Real-time field control systems could have a substantially beneficial impact on T2*w imaging, R2* mapping, SWI, and QSM at high magnetic field strengths.

References [1] Gelderen et al. Magn Reson Med 2007;57:362–368 [2] Barmet et al., MRM, 2009, 62:269-76 [3] Wilm et al., MRM 2011; 66(5):1690- 1701 [4] Vannesjo et al., Proc. ISMRM 2012; p.216 [5] Duerst et. al, MRM (2014), doi: 10.1002/mrm.25167 [6] M.Wyss et. al, Proc. #3249 ISMRM 2014 [7] Zhu et al., OPTICS LETTERS 28(14):1194-95 (2003) [8] Schweser et al., Magnetic Resonance in Medicine 69:1582–1594 2013 [9] Özbay et. al, # 3171 Proc. ISMRM 2014 [10] SPM analysis toolbox (UCL, London, UK) [10] SPM analysis toolbox (UCL, London, UK)