Flow Compensated Quantitative Susceptibility Mapping for Venous Oxygenation Imaging

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PURPOSE: To correct flow induced artifacts in quantitative susceptibility mapping (QSM) to allow brain venous oxygenation measurement. A full 3D flow compensated multi-echo gradient echo sequence is combined with a higher order polynomial fit of the resulting multi-echo phase data. The preliminary results demonstrate the feasibility of estimating venous oxygenation.

METHODS: ***1) Theory*:** When flow is present, MRI signal equation is written as:

$$s(t) = \int \rho(\mathbf{r}(0)) e^{-i(\psi+\gamma\int_0^t \delta B(\mathbf{r}(\tau)))d\tau} e^{-i\gamma\int_0^t \mathbf{G}(\tau)\bullet\mathbf{r}(\tau)d\tau} d\mathbf{r} = \int \rho(\mathbf{r}(0)) e^{-i\phi 1} e^{-i\phi 2} d\mathbf{r} \quad [1]$$

where $s(t)$ is acquired signal, $\mathbf{r}(t)$ is the spin position, ψ is the initial phase after rf pulse, $\rho(\mathbf{r})$ is the spin density, $\delta B(\mathbf{r})$ is the field inhomogeneity at position $\mathbf{r}(t)$, and $\mathbf{G}(\tau)$ is the gradient field. During k-space sampling, for $0<\tau<TE$, the velocity field $\mathbf{v}(\mathbf{r}(\tau)) \sim$ constant, $\mathbf{r}(\tau)=\mathbf{r}(TE)+\mathbf{v}(\mathbf{r}(0))(\tau-TE)$. Assuming that $\delta B(\mathbf{r})$ is locally linear: $\delta B(\mathbf{r})=\delta B(\mathbf{r}_0)+(\mathbf{r}-\mathbf{r}_0)\bullet\nabla\delta B(\mathbf{r}_0)$, then ϕ_1 and ϕ_2 become:

$$\phi_1 = \psi+\gamma\cdot\delta B(\mathbf{r}(TE))\cdot TE-\tfrac{1}{2}\cdot\gamma\cdot\mathbf{v}(\mathbf{r}(0))\bullet\nabla\delta B(\mathbf{r}(TE))\cdot TE^2 \quad [2]$$

$$\phi_2 = \mathbf{r}(TE)\bullet\mathbf{k}(TE)+\gamma\cdot\mathbf{v}(\mathbf{r}(0))\bullet\mathbf{M}(TE) \quad [3]$$

where $\mathbf{k}(TE)$ is the k-space position and $\mathbf{M}(TE)$ is the first moment of $\mathbf{G}(\tau)$ at time TE. The phase ϕ_1 is a quadratic function of TE, where the linear coefficient is the local field inhomogeneity. In Eq [3], the extra phase term containing $\mathbf{M}(TE)$ is removed by using a full 3D flow compensation gradient[1,2].

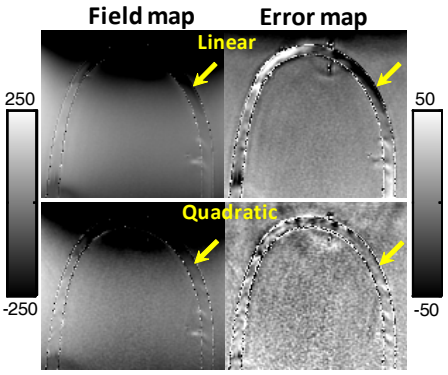

Fig. 1 Field and error map (in Hz) of linear and quadratic fit using proposed sequence

***2) Acquisition and reconstruction*:** A 3D multi-echo fast spoil gradient echo sequence is used. In addition to readout gradient flow compensation, the proposed sequence has flow compensation gradients added for each echo and for each encoding direction (ky,kz). Both a linear fit $\phi_1=\psi+L\cdot TE$ and quadratic fit $\phi_1=\psi^*+L^*\cdot TE+Q^*\cdot TE^2$ were performed. The field inhomogeneity $\gamma\cdot\delta B(\mathbf{r})$ was taken to be the coefficient of the linear term. In order to improve the noise performance, a hybrid linear-quadratic fit was developed to ensure that the quadratic fit was only used in those locations exhibiting flow. The model computes a linear combination of the linear coefficients of the two fits: $\gamma\cdot\delta B(\mathbf{r})=(1-w)L+wL^*$, where $w=1-e^{-\alpha|(L-L^*)Q^*|}$ and $\alpha=0.01$. The resulting field inhomogeneity map served as the input for MEDI with nonlinear formulation[3] (MEDIN), a dipole deconvolution algorithm, to compute the susceptibility or QSM image. ***3) Phantom validation*:** A U-shaped tube connected to a pump was fixed inside a plastic box which was filled with tap water and put inside the scanner bore. Constant flow of known magnitude was generated by the pump. A reference image was obtained when flow was set to 0. A second identical scan was performed with a 12cm/s flow rate, with the proposed full 3D flow compensated sequence. A linear and quadratic fit were performed and compared with the reference field map obtained from the zero flow reference images. ***4) In vivo study*:** N=8 human subjects were scanned with the proposed sequence on a 3T scanner (GE Healthcare). Scan parameters are: 7 echoes, $TR/TE_{first}/TE_{last}$ =48.2/3.7/43.8ms, FA=20°, voxel size = 0.7×0.7×0.7mm^3. Two QSM images were reconstructed using the field map from the linear fit and the proposed hybrid fit, respectively. Major veins were identified and the number of visualized cortical veins was compared between the two fitting methods. Venous oxygen saturation fO_2 was computed according to $\chi_{blood}=Hct(1-fO_2)\Delta\chi_{do}$, where Hct=0.4 and $\Delta\chi_{do}$=2.26ppm [4].

RESULTS: In Fig.1, a comparison of the inhomogeneity field between zero and non-zero flow shows that the quadratic fit greatly improves the field estimation in the presence of both flow and spatially varying fields. The estimated inhomogeneity field inside the tube has a significantly reduced error when compared to the static zero flow acquisitions. Fig. 2 shows a Maximum Intensity Projections (MIP) of a 10mm-thick slab from the obtained QSM in one healthy volunteer. Small veins missing in the linear fit result were recovered by hybrid fit method. The conspicuity and sharpness of a number of dim and disconnected appearing veins were improved using the hybrid fit. In all volunteers, more cortical veins were visualized using the proposed hybrid fit method than with the linear fit method (Fig. 3). In six major cortical veins, the estimated venous oxygenation level was 74%±3% from the hybrid fit, while the linear fit exhibited 94%±6% oxygenation level, which is likely an overestimation.

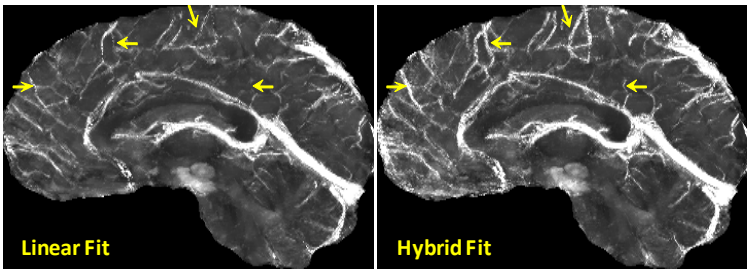

Fig. 2 In vivo QSM MIPs from linear fit and hybrid fit

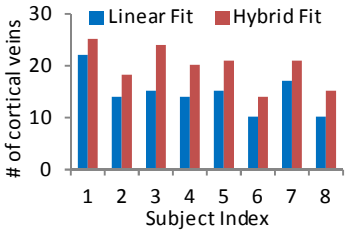

Fig. 3 Number of cortical veins from linear and hybrid fit for all subjects

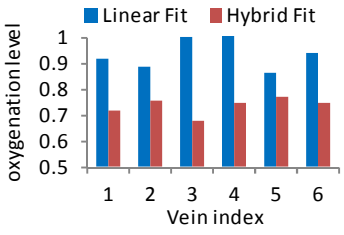

Fig. 4 Venous oxygenation level in major cortical veins from both methods

DISCUSSION AND CONCLUSION: The presence of flow and spatial varying inhomogeneity field introduces artifacts in the estimation field map and QSM leading to reduced reliability of the estimated susceptibility in vessels. Using hybrid linear-quadratic fit of the multi-echo phase images, the field inhomogeneity map is greatly improved. Vein depiction on QSM is similarly improved. This has the potential to lead to more accurate venous oxygenation quantification.

REFERENCES: [1] Bernstein et al. JMRI 1992; 2:583-588. [2] Slavin et al. MRM 1997; 38:368-377. [3] Liu et al. MRM 2012, DOI: 10.1002/mrm.24272. [4] Weisskoff et al. MRM 1992; 24, 375-383