Regularized Quantitative Susceptibility Mapping for Phase-based Regional Oxygen Metabolism (PROM) at 7T

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Introduction: Venous oxygen saturation (Y_v) and oxygen utilization are important indicators for brain function and disease, and absolute quantification of Y_v may provide critical information to better understand the BOLD signal and quantify cerebral metabolic rate of oxygen ($CMRO_2$) [1,2]. MR susceptometry has been used to measure the susceptibility difference between veins and the surrounding tissue, from which Y_v can be quantified [3]. This approach has provided valuable estimates of oxygenation in large draining veins of the brain [1] and in cerebral pial veins [2,4]. However, to simplify susceptibility measurements, MR susceptometry has depended on the assumption that vessels approximate long cylinders parallel to the main magnetic field. This assumption restricts the set of veins amenable to the technique and may introduce bias to Y_v estimates depending on how well the model holds. In general, reconstruction of the susceptibility distribution (χ) from a field map is an ill-posed problem because the dipole kernel in k-space undersamples the measured field [5]. Because the gradient of underlying susceptibility distribution is sparse, using an appropriate prior to promote sparsity may yield high quality reconstruction of χ even from undersampled data [5,6]. Here we implement l_1-regularized quantitative susceptibility mapping (QSM) to estimate Y_v in cerebral veins at 7T without assumptions about vessel geometry. Y_v estimates from MR susceptometry and QSM are compared, and Y_v measurements are extended to curved, in-plane segments of cerebral veins.

Methods: Five healthy volunteers (mean age 28 ± 5 years, 3 females and 2 males) were scanned with a 32-channel head coil using a 7T Siemens magnet. A 3D flow-compensated FLASH sequence was used to acquire axial magnitude and phase images (resolution = 0.33x0.33x1.0 mm^3, FOV = 192x168x64 mm^3, TE = 10ms). From the 3D phase image (φ), the normalized field map was determined as $\delta = \varphi/(\gamma \cdot TE \cdot B_0)$ where γ is the gyromagnetic ratio and B_0 is the main field strength. To reconstruct an estimate of the 3D susceptibility distribution from δ, an l_1 minimization approach was formulated as in Eq 1 [5, 6]. Here, F is the fast Fourier transform operator, D is the dipole kernel in k-space, G is the gradient operator, and M is a diagonal matrix that has value 1 for voxels corresponding to the brain and is 0 elsewhere. λ is the weighting of the l_1 penalty and was optimized as $\lambda = 10^{-3}$ for this dataset. Optimization in MATLAB was performed using a non-linear conjugate gradient approach with 50 iterations.

$$\hat{\chi} = argmin_{\chi} \left\| M\left(F^{-1}DF\chi - \delta\right)\right\|_2^2 + \lambda \left| M\left(G\chi\right)\right|_1 \quad (1)$$

Three veins were manually identified in each subject such that each vessel had a segment parallel to the main magnetic field and a curved, in-plane segment. For the parallel segment (Fig 1a,b), the field difference ΔB between the candidate vein and tissue was determined from the phase images. MR susceptometry was then used to estimate the susceptibility difference as $\Delta\chi_{vein\text{-}tissue} = 6 \cdot \Delta B / [4\pi \cdot B_0 \cdot (3\cos^2\theta - 1)]$, where θ=0 is the angle between the vessel and the main field. In each parallel vessel segment, the same ROI was used to also directly measure $\Delta\chi_{vein\text{-}tissue}$ from the susceptibility map reconstructed with the QSM algorithm described above (Fig 1c). Using $\Delta\chi_{vein\text{-}tissue}$ measured from both techniques, venous oxygenation was estimated as $Y_v = 1 - \Delta\chi_{vein\text{-}tissue}/(\Delta\chi_{do} \cdot Hct)$. Here $\Delta\chi_{do} = 0.18ppm$ is the susceptibility difference between fully deoxygenated and fully oxygenated blood [3], and hematocrit values were assumed, $Hct = 0.42$ for males and $Hct = 0.38$ for females [7]. In contrast, Y_v estimates could not be made for in-plane vein segments using MR susceptometry because the vessel geometry and orientation did not fit the assumed cylinder model. To quantify oxygenation in these vessels, $\Delta\chi_{vein\text{-}tissue}$ and thus Y_v were estimated directly from the reconstructed χ map (Fig 2).

Results: Table 1 presents the mean absolute Y_v quantified for each subject. For vessel segments parallel to the main magnetic field, a mean Y_v of 62.1±2.2% was measured using MR susceptometry and a mean Y_v of 61.2±2.6% was measured using l_1-regularized QSM across subjects. These values agree well with previously reported values of 64±4% from MR susceptometry in the sagittal sinus [1] and 59.4±6% using ^{15}O positron emission tomography [8]. In addition, no significant difference (p=0.11) was detected between Y_v estimates from MR susceptometry and from QSM in parallel vein segments. From the reconstructed susceptibility maps, we estimated a mean Y_v for in-plane vessel segments of 66.7±2.8%, which also lies in the physiological range. Y_v measured from in-plane segments tended to be higher than Y_v from parallel segments of the same vein, which may reflect partial volume errors for in-plane measurements with anisotropic resolution. Future work will investigate the relationships between our QSM measurements, resolution, and vessel diameter to improve accuracy of Y_v estimates.

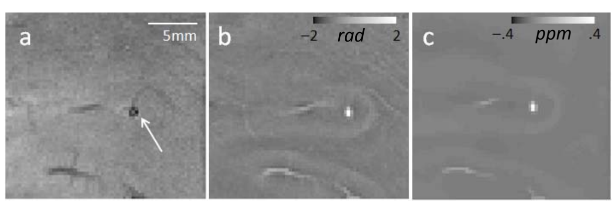

Figure 1. Axial slice with vein segment parallel to main magnetic field. **(a)** Magnitude; **(b)** Phase; **(c)** Estimated susceptibility from QSM.

Conclusion: We have demonstrated the feasibility of QSM for robust estimates of absolute Y_v at 7T for vessels of arbitrary orientation and curvature.

Table 1. Absolute venous oxygenation, Y_v (%)

Subject	Susceptometry	QSM Parallel segments	QSM In-plane segments
1	60.7	59.1	67.9
2	59.1	57.7	61.8
3	64.3	62.5	68.4
4	62.5	63.0	67.8
5	63.8	63.7	67.4
Mean ± SD	**62.1 ± 2.2**	**61.2 ± 2.6**	**66.7 ± 2.8**

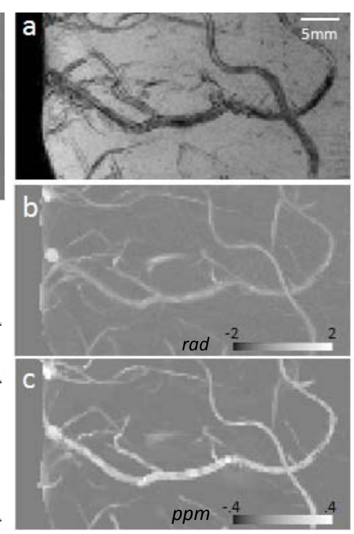

Figure 2. Axial slice with in-plane vessel segment. **(a)** Magnitude; **(b)** Phase; **(c)** Estimated susceptibility.

References

1. Jain V, JCBFM 2010; 30:1598-1607
2. Fan AP, ISMRM 2010; 693
3. Weiskoff RM, MRM 1992; 24(2):375-383
4. Haacke EM, HBM 1997; 5:341-346
5. Liu J, ISMRM 2010; 4996
6. Lustig M, MRM 2007; 58(6):1182-95
7. Guyton, Textbook of medical physiology
8. Ishii K, J Nucl Med 1996; 37:1086-88

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