SUSCEPTIBILITY AND CROSS-SECTIONAL AREA QUANTIFICATIONS OF SMALL VEINS IN HUMAN BRAIN

Ching-Yi Hsieh[1], Yu-Chung Norman Cheng[1], Jaladhar Neelavalli[1], and E. Mark Haacke[1]
[1]*Wayne State University, Detroit, MI, United States*

Target audience: physicians and scientists interested in noninvasive imaging of venous oxygenation in the brain.

Purpose: Changes in venous blood oxygenation levels lead to direct changes in the magnetic susceptibility of veins. The oxygenation saturation level reflects the physiological state of a given vein [1]. Therefore, measuring oxygen saturation level may provide an important diagnostic tool. Recently several groups have developed methods to quantify the susceptibility of human veins [2,3,4]. Here, we provide the alternative approach to quantifying the susceptibility of human veins using the overall MR signal surrounding a cylindrical object. In addition, our method provides solutions of practical issues-local background phase, low SNR of the object, and the object at the low orientation.

Method: Our previous work [5] has accurately quantified effective magnetic moments of given cylindrical objects. The effective magnetic moment is defined as $p \equiv g'a^2$, where $g' \equiv g \sin\theta^2$, $g \equiv 0.5\gamma B_0 \Delta\chi$, a is the radius of an object and θ is the orientation of the cylinder to the main field, γ is the gyromagnetic ratio, $2\pi \cdot 42.58$ MHz/T, and $\Delta\chi$ is the magnetic susceptibility of the object. When an object of interest (e.g. vein) has an MR signal, the susceptibility of the object can be quantified by equation 1, and its volume may be uniquely quantified by the known magnetic moment and susceptibility values. For the susceptibility quantification of veins, the signal to noise ratio, SNR, inside veins can be low at long echo times, TEs. The lower the SNR inside the vein is, the larger the uncertainty of the measured susceptibility is. Using gradient echo images from two echoes, long and short TE, can reduce the uncertainty of the susceptibility quantification. We can first quantify the magnetic moment, *p*, of a given vein using equation 11 of the reference [5] from the longer TE. Then we scale the magnetic moment to the shorter TE and solve the susceptibility of the same vein using equation 1 at the shorter TE because of higher SNR inside the object at the shorter TE. At the low orientation such as 30 degree to the main field, the magnetic moment of the *in-vivo* object is so small that equation 1 is approximately equal to equation 2, and acquiring images at two TEs. Using equation 3 solves the susceptibility. After applying background removing techniques, the existing local background field could still cause a discrepancy when attempting to identify the center of the object and $\Delta\chi$ in our method. Thus, we need to take this potential discrepancy into account in our equations. We assume that the phase induced by other tissues in the local area around the vein of interest is a constant, φ_{bkg} so the complex signal S becomes $U=S\, e^{i\varphi bkg}$. Therefore, we can estimate the local background phase from the annular region of two concentric radii. After φ_{bkg} is estimated, we subtract φ_{bkg} from the phase image, and then sum up the complex signals. The uncertainties of the magnetic moment, susceptibility, and cross-sectional area were calculated through the error propagation method. We applied our methods to several isolated veins (see Figs. 1) from branches of anterior, inferior, superior cerebral veins, and transverse sinus, and from two sets of existing MR images [2]. A 3D gradient echo single-echo sequence with velocity compensation in all three directions was used for the acquisitions of both datasets. One set of the images were acquired from a female volunteer utilizing and within a 3.96 T Bruker machine. A single channel birdcage head coil was used in this case. The imaging parameters were: isotropic resolution 0.5 mm, TE = 11.6 ms and 19.2 ms, repetition time = 26.0 ms, flip angle = 11°, read bandwidth = 120 Hz/pixel and field of view = 256 mm × 176 mm × 45 mm. The scan was performed twice, but individually for each echo time.

Result: Our quantified susceptibility values shown in Tab. 1 in general agree with values (0.37-0.54 ppm) from other recent work [3,4]. Our susceptibility values of 5 veins in different regions of a volunteer brain in Fig. 1 are close to each other. The number of vein appears in Fig. 1 corresponds to results listed in Tab. 1. The typical susceptibility value from a vein of a healthy person is about 0.41 ppm, if we assume an oxygenation level of 70%, a Hemoticrit of 40%, and a susceptibility difference between fully deoxygenated blood and oxygenated blood of 3.39 ppm [6]. From the measured cross-sectional area of each vein in Tab. 1, we find that in most cases the diameter of each vein is just a little bit more than one pixel. For veins at low orientations, we have quantified one vessel with orientations of 10° at TE = 11.6 ms from 3.96 T images. The susceptibility value of this vein is 0.48 ± 0.02 ppm and its cross-sectional area is 5.64 ± 1.58 pixel^2.

Conclusion: According to *in-vivo* results here, our method can successfully quantify the susceptibility and cross-sectional area of objects and reduce the uncertainty under local background phase, low SNR of the object and the object at low orientations.

$$Re(S)\sin\phi_{in} = Im(S)\cos\phi_{in} + \pi\ell\rho_0\wp\sin\phi_{in}\int_{\wp/R^2}^{g'} dx J_0(x)/x^2 \qquad (1)$$

where Re(S) is the real part of the complex signal S, Im(S) is the imaginary part of S, and ρ_0 is the spin density surrounding the object. $\varphi_{in} \equiv g/3\ (1\text{-}3\cos\theta^2)$ is the phase value inside the object. After solving $\Delta\chi$, we can solve radius, a, from $\sqrt{(p/g')}$.

$$Re(S_n)\sin\phi_{in,n} = Im(S_n)\cos\phi_{in,n} + \pi\ell\rho_{0,n}\sin\phi_{in,n}\left(R^2 + \frac{g_n'^2 a^4}{4R^2} - a^2 - \frac{g_n'^2 a^2}{4}\right) \qquad (2)$$

where the subscript n is referred to as each variable obtained at the nth TE_n. We solve each $\rho_{0,n}$. Then using images from different TE's, we can solve $\Delta\chi$ of the object from equation 3 through an iterative procedure.

$$\begin{aligned}(\rho_{0,2}Re(S_1) - \rho_{0,1}Re(S_2))\sin(\phi_{in,1})\sin(\phi_{in,2}) &= \pi\ell\rho_{0,1}\rho_{0,2}\sin(\phi_{in,1})\sin(\phi_{in,2})\frac{a^2}{4}\left(1 - \frac{a^2}{F^2}\right)(g_2'^2 - g_1'^2) \\ &+ \rho_{0,2}Im(S_1)\sin(\phi_{in,2})\cos(\phi_{in,1}) - \rho_{0,1}Im(S_2)\sin(\phi_{in,1})\cos(\phi_{in,2}) \qquad (3)\end{aligned}$$

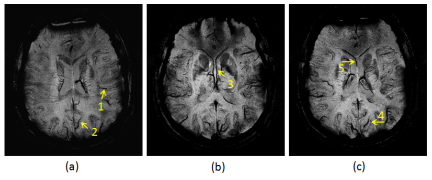

Fig. 1 SWI mIP over 8 slices @ TE=19.2 ms

Angle (Degree)	$\wp$ rad·pixel^2	$\Delta\chi$ ppm	A_0 pixel^2
80 ± 3	1.26 ± 0.76	0.47 ± 0.16	1.41 ± 1.18
90 ± 1	2.01 ± 0.64	0.45 ± 0.11	2.27 ± 1.43
75 ± 3	1.98 ± 0.71	0.46 ± 0.13	2.38 ± 1.71
70 ± 3	1.22 ± 0.39	0.48 ± 0.22	1.45 ± 0.99
70 ± 3	1.35 ± 0.38	0.48 ± 0.20	1.63 ± 1.08

Tab. 1 magnetic moment, susceptibility and cross-sectional area of five veins

Ref: [1] Ogawa, Biophys. J.(1993), pp.803-812 [2] Haacke, JMRI, 2010, pp.663-676. [3] Fan, MRM, 72, pp.149-159. [4] Xu, MRM, 72, pp. 438-445. [5] Cheng, PMB, 54, pp.7025-7044. [6] Spees, MRM, 45, pp. 553-542. Funding: NIH/NHIBI 108230-01A2