Phase-based Regional Oxygen Metabolism (PROM) at 3T and feasibility at 7T

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Introduction: The cerebral metabolic rate of oxygen ($CMRO_2$) is an important indicator for brain function and disease, including stroke and tumor. $CMRO_2$ can be quantified from measurements of venous oxygen saturation (Y_v) and cerebral blood flow (CBF) in cerebral veins. Bulk susceptibility measurements based on gradient-echo phase maps have been used to estimate Y_v *in vivo* at 3T [1]. Challenges of this technique include partial volume effects, phase wrapping, and background susceptibility gradients. Here we quantify $CMRO_2$ by independently measuring Y_v and CBF at 3T using MR susceptometry and arterial spin labeling (ASL). We also demonstrate feasibility of quantifying Y_v at 7T, which offers higher-resolution analysis of vessels of interest.

Methods: A flow-compensated, 2D GRE sequence was used to acquire axial magnitude and phase images at 3T (0.5-mm resolution in-plane, 2.0-mm thick, FOV 224 x 224 mm^2). Data were collected for TEs of 10, 15, 20, and 25 ms. Local regions of interest (32 x 32 pixels) containing veins perpendicular to the slice were manually identified. The phase of the ROI was high-pass filtered (32 x 32 Hanning [2]).

The average phase difference ($\Delta\varphi$) between the inside of the vein and the surrounding tissue was measured for each TE. The corresponding field difference, $\Delta B = B_{vein} - B_{tissue}$, was calculated by a linear fit of the measured $\Delta\varphi$ vs. TE. The oxygen saturation Y_v was then determined from ΔB through Eq 1, where $\Delta\chi_{do} = 0.18$ppm (cgs) is the susceptibility difference between fully deoxygenated and fully oxygenated blood, and $Hct = 0.4$ is the assumed hematocrit value [1].

$$\Delta B = \frac{1}{3} 4\pi \Delta\chi_{do} \, Hct \cdot (1 - Y_v) B_0 \qquad (Eq.1)$$

$$CMRO_2 = \frac{Y_a - Y_v}{Y_a} \frac{Hct}{3.0 \cdot 1.6125} \cdot CBF \cdot Y_a \qquad (Eq.2)$$

To measure CBF, a PICORE-Q2TIPS pulsed ASL acquisition was used with 3.5-mm in-plane resolution and 4.0-mm slice thickness. To calibrate the CBF measurement, the fully relaxed longitudinal magnetization of arterial blood (M_{0B}) was estimated from the local tissue equilibrium magnetization [3]. $CMRO_2$ (μmol/g/min) was determined for five vessels from one healthy subject using Eq 2 [4], where the arterial oxygen saturation was assumed to be $Y_a = 1$.

At 7T, a 3D GRE sequence was used to acquire axial images with 0.33 mm in-plane resolution, 1.0 mm slice thickness and FOV of 192 x 168 mm^2, for TE's of 10, 14, and 20 ms. The phase images were unwrapped using FSL *prelude* [5] and high-pass filtered with a Gaussian kernel [6]. Y_v was quantified for ten vessels from one healthy subject at rest using Eq 1.

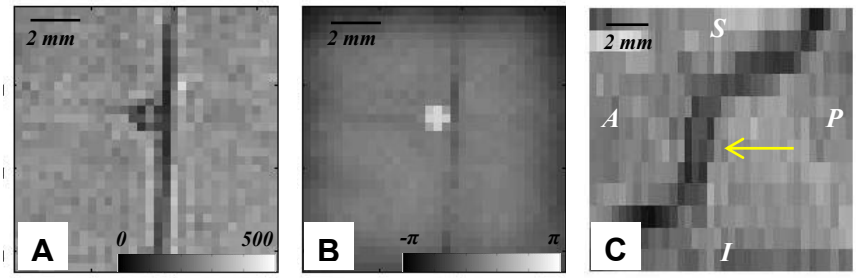

Fig 1. (A,B) Magnitude and filtered phase of ROI with through-plane vein for TE = 10ms at 7T. (**C**) Sagittal magnitude of vein 1. Arrow denotes slice used for measurements.

Vein	R^2 of linear fit	$\bar{Y}_v$	CBF (ml/100g/min)	$CMRO_2$ (μmol/g/min)
1	0.99	0.54	49.3	1.86
2	0.99	0.53	48.7	1.89
3	0.96	0.64	49.1	1.48
4	0.96	0.66	49.4	1.39
5	0.97	0.59	49.0	1.67
Average		***0.59 ± .06***	***49.1 ± 0.3***	***1.66 ± 0.22***

Table 1. Y_v, CBF, and $CMRO_2$ determined for five veins at 3T.

Results: Through-plane vessels from various slices were identified from magnitude images at 3T and 7T. ROI's from 7T are shown in Fig 1. After filtering the phase ROI, the average $\Delta\varphi$ between the vein and the surrounding tissue was determined for each TE (Fig 1B). A sagittal view of the vessel (magnitude) was used to confirm that the vessel was perpendicular to the slice (Fig 1C). For each vessel, the linear fit of $\Delta\varphi$ versus TE was robust, yielding R^2 values >0.95. Y_v measurements were consistent across several adjacent slices to which the vessel was approximately perpendicular. The Y_v was determined for ten veins at 7T, yielding a mean oxygenation value $\bar{Y}$ = 0.61±0.04, which lies in the expected physiological range.

Y_v and CBF were determined for five vessels in a healthy subject at 3T (Table 1). The CBF for each vein was measured by averaging values from a 7 mm^2 region that included the vessel of interest. The mean CBF was 49.1 ml/100g/min, which is consistent with the normal physiological range. $CMRO_2$ was then quantified for each vein using Eq 2 as described above. The mean $CMRO_2$ across the five vessels was 1.66 ± 0.22 μmol/g/min, which lies in the range reported for $CMRO_2$ by PET [7].

Conclusion: We have combined phase-based measurements of venous oxygen saturation (Y_v) with ASL measurements of cerebral blood flow (CBF) to quantify the cerebral metabolic rate of oxygen ($CMRO_2$) in cerebral vessels at 3T. Further, we extended estimates of Y_v to 7T, achieving a 1/5 reduction in voxel size. The improved spatial resolution allows examination of smaller vessels expected to be more indicative of regional brain function. Future work includes the extension of PROM to $CMRO_2$ estimates at 7T.

References: [1] Haacke EM, HBM (1997) 5:341-346. [2] Yu Y, Proc Int Soc Magn Reson Med, 1999. [3] Çavuşoğlu M, Magn Reson Imaging (2009) 27: 1039-1045. [4] van Zijl PC, Nat Med (1998) 4:159-167. [5] Jenkinson M, MRM (2003) 49:193-197. [6] Rauscher A, Magn Reson Imaging (2003) 18:175-80. [7] Sobesky J, Stroke (2005) 36:980-985. ***Acknowledgements:*** *Siemens Medical Solutions, HST Martinos Catalyst Fund, NIH RO1 EB007942, PHS T90 DA022759.*