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

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Introduction: The cerebral metabolic rate of oxygen (CMRO₂) is an important indicator for brain function and disease, including stroke and tumor. CMRO₂ can be quantified from measurements of venous oxygen saturation (Yᵥ) and cerebral blood flow (CBF) in cerebral veins. Bulk susceptibility measurements based on gradient-echo phase maps have been used to estimate Yᵥ in vivo at 3T [1]. Challenges of this technique include partial volume effects, phase wrapping, and background susceptibility gradients. Here we quantify CMRO₂ by independently measuring Yᵥ and CBF at 3T using MR susceptometry and arterial spin labeling (ASL). We also demonstrate feasibility of quantifying Yᵥ 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 mm²). 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 (Δφ) between the inside of the vein and the surrounding tissue was measured for each TE. The corresponding field difference, ∆B = Bᵥ - Bₜissue, was calculated by a linear fit of the measured Δφ vs. TE. The oxygen saturation Yᵥ was then determined from ∆B through Eq 1, where ∆χᵥ = 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].

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 (M₀B) was estimated from the local tissue equilibrium magnetization [3]. CMRO₂ (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 Yₐ = 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 mm², 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]. Yᵥ was quantified for ten vessels from one healthy subject at rest using Eq 1.

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 Δφ 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 Δφ versus TE was robust, yielding R² values >0.95. Yᵥ measurements were consistent across several adjacent slices to which the vessel was approximately perpendicular. The Yᵥ was determined for ten veins at 7T, yielding a mean oxygenation value Ȳ = 0.61 ± 0.04, which lies in the expected physiological range.

Yᵥ 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 mm² region that included the vessel of interest. The mean CBF was 49.1 ml/100g/min, which is consistent with the normal physiological range. CMRO₂ was then quantified for each vein using Eq 2 as described above. The mean CMRO₂ across the five vessels was 1.66 ± 0.22 µmol/g/min, which lies in the range reported for CMRO₂ by PET [7].

Conclusion: We have combined phase-based measurements of venous oxygen saturation (Yᵥ) with ASL measurements of cerebral blood flow (CBF) to quantify the cerebral metabolic rate of oxygen (CMRO₂) in cerebral vessels at 3T. Further, we extended estimates of Yᵥ 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 CMRO₂ estimates at 7T.