Three-dimensional mapping of brain venous oxygenation using T2-oximetry

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Target Audience: MR physicists and clinicians interested in blood oxygenation mapping in the brain.

Purpose: Brain oxygen metabolism is an important indicator of the brain's function and dysfunction. Quantification of brain oxygen consumption requires accurate measurement of venous oxygenation level, which is undergoing intensive research with different approaches in recent years [1-3]. One promising approach is based on a calibratible relationship between blood transverse relaxation times (T_2 or T_2*) and oxygenation level [4, 5]. This line of research began with a single location measure (giving a global value only) [6], and was later extended to a 2D slice along the sagittal sinus [1]. However, to date, three-dimensional measurement has not been reported. This is mainly because the CPMG-T_2 based methods used in the previous reports are limited by high SAR and long scan duration, thereby making it impractical for 3D acquisitions. In the present work, we developed a novel implementation of the T_2-based oximetry method and, for the first time, showed a 3D map of blood T_2* and oxygenation in the human brain.

Method: *Pulse sequence:* Figure 1 shows the pulse sequence diagram. This technique has three main concepts/steps. 1) It first utilizes the phase contrast method to separate blood signal from static tissue (blue in Fig. 1). This module is critical in minimizing partial volume effect so that the measured signal is only from blood but not tissue. 2) A multi-echo gradient-echo acquisition is performed to collect images as a function of TE. The sequence is fully flow-compensated in all echoes (purple) and the sampling of the k lines was in the same direction using a fly-back gradient (yellow), thereby avoiding vessel misalignment between echoes. The multi-echo images can then be used to estimate T_2* of pure blood on a voxel-by-voxel basis. 3) The measured blood T_2* is converted to oxygenation level using an in vitro calibration curve [5].

Experiment: Three healthy subjects (25-27 yo, 1F) were scanned on a 3T MRI scanner (Philips). The imaging parameters were: 4 echoes; TR= 60 ms; 1st TE/delta TE = 13 ms/14 ms; matrix size = 288 x 288 x17; resolution = 0.7 x 0.7 x 5 mm^3; sagittal slice orientation; flip angle = 15°; bandwidth = 217 Hz/pixel; V_{enc} = 9 cm/s; flow encoding direction: anterior-posterior; acquisition time = 9:48 min. Each subject was scanned twice to access the reproducibility of the method.

Data analysis: Complex images were obtained. The two images with the reversing bipolar flow-encoding gradients were subtracted in the complex space to obtain a "Complex Difference (CD)" image, for each echo. The importance of the CD image is that it does not contain any static tissue signal, but only reflects the blood signal. Eddy current effects were corrected based on [7]. This method fits the residual tissue phase due to eddy currents to a 3D hyperplane, which is then subtracted from the vessel phase. The procedure was performed separately for each echo, as eddy current effects are different for different echoes. The CD signal intensity was then fitted to a mono-exponential function of TE, yielding T_2* of pure blood. The T_2* was converted to oxygenation value (in % O_2 saturation) using a calibration plot reported previously [5].

Result and discussion: An example of the original images is shown in Figs. 2a and b, and the CD images are shown in Figs. 2c-f for different echo-times. The echo time is marked in red at the lower left corner. It can be seen that, with our V_{enc} and spatial resolution, both large (e.g. sinuses) and small vessels (e.g. 1-2 mm in diameter) are discernable in the CD image, but not in the originals. Figure 3 displays blood T_2* maps in one subject, with two repeated scans. It is apparent that veins and arteries can be clearly separated by their T_2* times – veins have T_2* values around 30 ms whereas arteries have T_2* values around 50 ms. The 3D acquisition allowed us to more completely evaluate the venous structure compared to previous 2D methods, especially for veins off the mid-sagittal plane, such as transverse sinus (green arrows) and superior anastomic veins (yellow arrows). It can also be seen from Fig. 3 that the test-retest reproducibility of the blood T_2* maps are excellent. Figure 4 shows ROI analysis results of venous T_2* (b) and oxygenation (c) at 5 anatomic locations. The oxygenation values measured are within physiological range and consistent with previous results using 2D methods [4]. There seems to be gradual reduction in venous oxygenation in anterior-to-posterior direction, in both cortical and deep brain regions.

Conclusions: In summary, we developed a method for 3D venous oxygenation mapping in the human brain. This method is found to provide oxygenation values within physiological range and possesses excellent reproducibility. This method may have potential utility in evaluating focal ischemia in cerebrovascular diseases, for which traditional 2D methods are of limited value.

Acknowledgement: We would like to thank Mr. Austin Ouyang and Dr. Hao Huang for the assist on 3D display of the data.

Reference: [1] Krishnamurthy et al. MRM 71:979, 2014. [2] Fan et al. MRM 72:149, 2013. [3] Gauthier et al. Neuroimage 63:1353, 2012. [4] Lu et al. MRM 67:42, 2012. [5] Zhao et al MRM 58:592, 2007. [6] Lu et al. MRM 60:357, 2008. [7] Krishanmurthy et al. ISMRM 2014: 1012.

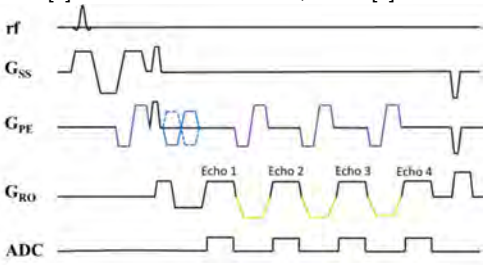

Fig.1. Diagram of the pulse sequence

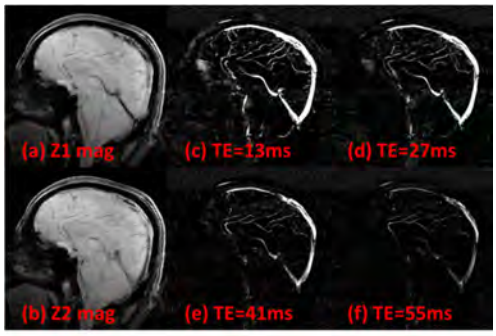

Fig.2. An example of original images in 4 echoes

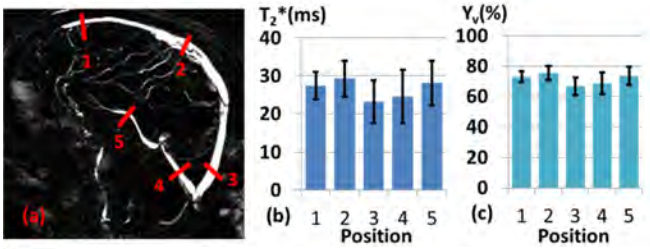

Fig.4. ROI analysis result of the venous T_2* and oxygenation

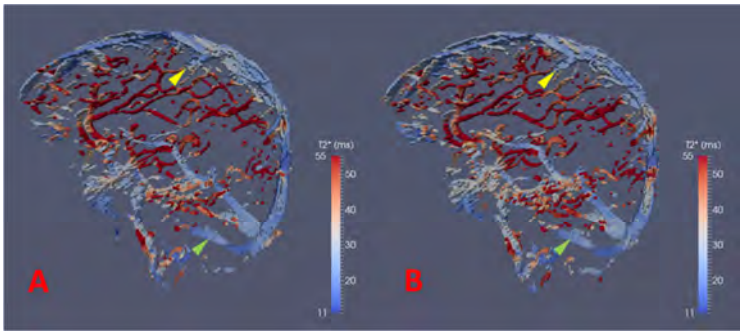

Fig.3. 3D display of the vessel T_2* map.