Vessel-specific mapping of cerebral venous oxygenation of small veins

Lisa C. Krishnamurthy,1,2 and Hanzhang Lu1

1Advanced Imaging Research Center, UT Southwestern Medical Center, Dallas, TX, United States, 2Dept. of Bioengineering, University of Texas at Arlington, Arlington, TX, United States

Target Audience
MR Physicists and Clinicians interested in venous oxygenation quantification, especially effect of artifact on accuracy.

Purpose
The ability to measure human brain metabolism on a routine basis will have a large impact on the diagnosis and treatment of brain disorders. A key component in quantitative metabolic imaging is the assessment of tissue oxygenation (Yv). Several potential approaches have been proposed to quantify Yv, including intravascular T2-based methods which rely on a simple and calibratable relationship between blood T2 and Yv. Recently we introduced such a T2-based method to measure Yv, along the major draining vessels of the brain called T2-Relaxation-Under-Phase-Contrast (TRU-PC) MRM. We showed that TRU-PC is a non-invasive, rapid, and reproducible method to measure vessel-specific Yv, but fell short of mapping the Yv of small veins (caliber of 1–2 mm). The ability to generate such a “small-vessel map” of Yv may help in better characterizing variations in venous oxygenation across brain regions, identifying regions at risk of ischemia attack or stroke, and may find immediate applications in clinical conditions that affect specific brain regions. The present study aims to optimize TRU-PC to generate a complete Yv map of the vasculature in the mid-sagittal brain, including small veins. The optimization includes removing an eddy-current induced artifact to improve the Yv quantification, performing multiple scans to sensitize the maps to vessels with different flow velocity and orientation, and merging these scans into a single, comprehensive Yv map.

Methods
Removing eddy-current induced artifact: The TRU-PC MRI technique applies the Phase Contrast (PC) principle4 to separate pure blood signal from the surrounding static tissue. The T2 value of pure blood is then determined using non-selective T2-preparation pulses, which minimizes the effect of flow on T2 estimation5. PC MRI applies two bipolar gradients in opposite directions in order to cancel out the tissue signal during complex subtraction of the images, resulting in a complex difference (CD) image. However, the application of flow-encoding bipolar gradients can generate eddy-currents that cannot be cancelled out by the application of an opposite bipolar gradient, resulting in an imperfect removal of tissue signal. This tissue signal will superimpose on the vessel signal, resulting in an inaccurate T2-quantification. We propose to use a method developed to remove field-imperfections6 to remove the arbitrary phase generated by eddy-currents. This correction will remove unwanted tissue signal and improve the T2-quantification of blood. We have proposed a simple linear combination of the true phase difference (Δθ) and a phase caused by eddy-currents (Δε): Δϕ = Δθ + Δε. We reconstruct the Δϕ images from the complex data4, and calculate a hyper-plane of field inhomogeneity (Δε) from the Δϕ images using all eTEs simultaneously for the fitting. By subtracting Δε from Δϕ, the true phase difference, Δθ, remains. By using the law of cosines4, the CD images are reconstructed using the true phase difference, Δθ. Sensitizing the Yv maps to more vessels: To acquire the complete vasculature in the mid-sagittal brain at 3T (Philips Achieva, 32 Ch. Receive headcoil), four separate TRU-PC scans were employed: one small- vessel scan with flow-encoding in anterior-posterior (AP) direction, one small-vessel scan with flow encoding in foot-head (FH) direction, and two large-vessel scans, also in AP and FH. The TR protocols for the large-vessel and small-vessel scans are similar, with the only difference being the flow-encoding cut-off velocity (Venc) (Vlarge=15 cm/sec, Vsmall=3 cm/sec for Female), and recovery time (RT) (RTlarge=475 ms, RTsmall=668 ms). The T2-preparation incorporates hard composite pulses; MLEV-16 phase cycled, with τ2=10 ms. This results in four sets of complex images with two effective TEs (eTE = 0 and 40 ms). Due to short blood T2*, the eTE was set to “shortest” with a conventional gradient echo (FOV = 200x200 mm2, acq matrix = 276x83, reconstruction matrix=400x400, 1 slice, slice thickness = 5 mm). The total scan time is ~15 minutes.

Results and Discussion
Figure 1 shows a representative scan. The CD image for each eTE was reconstructed individually for each of the four scans as described above. Then the signal intensity from the four scans was thresholded at an SNR of 2.5, and the voxel-wise T2 value was thresholded to be less than 140 ms based on venous blood T2 at 3T. Finally, the signal from all four scans was merged using sum-of-squares method, and the arteries were removed with a vein mask generated from Susceptibility Weighted Imaging (SWI)7. The T2-map was generated on a voxel-by-voxel basis along the entire vascular path using a mono-exponential model, where the signal from non-zero voxels within a 35x35 voxel block were incorporated in the T2-fitting to reduce error due to noise. The T2 was then converted to Yv using a known calibration plot8. Five subjects (3 Female/2 Male, age 21-40) were scanned twice with the entire protocol. We compare the results with and without eddy-current correction.

Conclusion
In summary, we have optimized TRU-PC MRI to obtain a complete map of Yv from the brain’s mid-sagittal draining veins (diameter of 1 mm or greater). This includes the removal of aberrant static tissue signal generated by eddy-currents, which improves the T2-quantification of venous blood signal. We have also sensitized our acquisition to many more vessels, and we have shown that a single complete Yv map can be generated from these scans. This improved vessel-specific Yv map provides a better region-specific measurement of oxygenation and metabolism in the brain.

References

Figure 1: The Δϕ and CD images before and after eddy-current correction for one eTE from a representative scan. Δϕ has units of radians, the


Figure 2: The T2 and Yv maps before and after eddy-current correction from a representative scan. The T2 map has units of ms, the Yv map has units of %.

Figure 3: A Yv map superimposed on the anatomical SWI magnitude image. SV=septal vein, ICV = internal cerebral vein, GV=great vein, SV=small sinun, ISS=superior sagittal sinus, ISS=inferior sagittal sinus, SSS=superior sagittal sinus.