Measuring Blood Volumes using CPMG Echo-space Dependence at 3T

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Introduction: This study aims to measure the CPMG echo-spacing dependence of in vivo brain tissues at rest, to investigate the possibility of using this effect to develop methods with which to measure the change in arterial[1] and venous blood volumes and oxygenation during neuronal activation. A voxel in brain tissue contains a blood volume component, the R_2 of which depends on the blood oxygenation. This blood component has been shown to display an echo time dependence[2]. The echo time dependence of the extravascular signals (due to diffusion in field gradients) is negligible at these echo times[3]. This study aims to use this dependence to estimate blood volume in mixed tissue voxels in the occipital cortex.

Theory: Blood R_2 is dependent on the echo-spacing (τ_{CP}) in a CPMG measurement sequence. This is thought to be due to exchange and/or diffusion between sites of different susceptibility in the erythrocytes and the plasma[4]. At very short echo spacings the dephasing is limited and the measured R_2 is close to its minimum value, R_{20}. As echo spacing increases, an exchange/diffusion term (R_{2exc}) contributes, leading to an increase in apparent R_2. This increase is higher for low blood oxygenation due to the effect of paramagnetic deoxyhaemoglobin, and so will be considerably more pronounced in venous blood compared to arterial blood. Assuming fast exchange between venous blood and tissue water, we can write the following expression for the signal from a mixed voxel:

$$S(T_e,(\tau_{cp})) = S_0(\exp(-T_e * R_{2voxel}(\tau_{cp}))) \quad \text{where} \quad R_{2voxel}(\tau_{cp}) = V * R_{2blood}(\tau_{cp}) + (1-V) * R_{2tissue} \qquad \textit{Equation1.}$$

and where *V* refers to the volume of blood contained within the voxel, $R_{2blood} = R_{20} + R_{2exc}$ and $R_{2tissue}$ refers to the relaxation of tissue containing no blood. Thus voxels containing a significant fraction of venous blood will exhibit R_2 changes dependent on the CPMG imaging sequence parameters.

Method: Three healthy volunteers were scanned using an in-house built 3T scanner, with a TEM coil for transmission and a surface receive coil (5cm diameter). Images were acquired with a 64x64 matrix, 2.5 kHz switching frequency, and with in-plane resolution of 2.5 mm x 3.5 mm, and 5.0 mm slice thickness. A multi-echo CPMG pulse sequence using paired hyperbolic secant 180^0 pulses for refocusing was employed. Interleaved image acquisition was implemented to reduce the minimum echo spacing (minimum τ_{CP} = 17ms). A repetition time of 8 s was used between acquisitions to allow complete recovery of signals. R_2 values were obtained for six values of τ_{cp}, from 17 to 24 ms. The number of echoes and averages acquired at each echo spacing was optimised for signal to noise[5]. The total experimental duration to acquire six echo spacings was 30 minutes. In addition in vitro blood samples were also imaged at 3 T, to investigate the echo dependence of pure blood R_2. A variety of blood oxygenations were studied, bubbling O_2 through the venous sample to oxygenate them. Images were acquired using the above CPMG sequence with a 32x32 matrix and switching frequency of 3.9kHz to reduce the minimum τ_{cp} to 13ms.

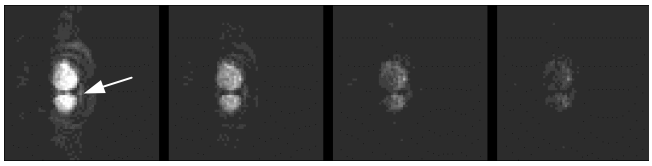

Figure 1: Multi-echo Images acquired for τ_{CP} =17 ms.

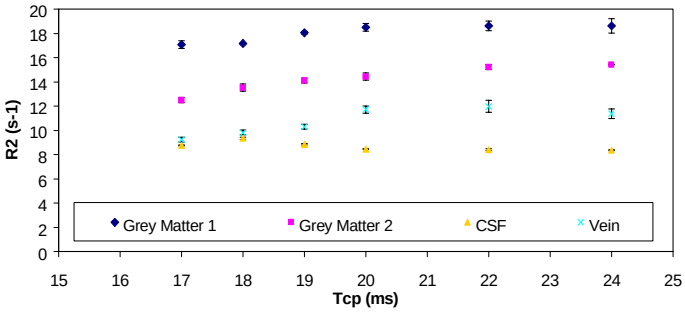

Figure 2: R2 vs τ_{CP} for occipital lobe ROIs.

Analysis: For each echo spacing, individual sets were averaged and multi-echo trains were obtained. Regions of interest were drawn in the sagittal sinus, grey matter and CSF. For these ROIs the R_2 was calculated for each echo spacing using a weighted, linear least square fit[5]. The sagittal sinus ROI was used to calculate $R_{2blood}(\tau_{cp})$ in each subject. The venous blood volume in each of the grey matter ROIs was calculated from Eqn. 1, using data at each τ_{cp} and assuming $R_{2tissue}$ =18.2 s^{-1} at 3 T.

Results: Figure 1 shows representative images acquired for a τ_{cp} of 17 ms (the arrow indicates the sagittal sinus). Figure 2 shows a plot of R2 versus echo spacing for each of the ROIs defined in the occipital lobe. Across all values of τ_{CP} the vein ROI has a lower R_2 than that of grey matter. As expected, the CSF ROI does not demonstrate an increase in R_2 with echo spacing. Fits for the blood volume fraction gave values of 0.24 for grey matter region1, and 0.63 for grey matter region2 of the occipital lobe.

Discussion: The echo-spacing dependence of brain tissues at 3T has been demonstrated in vivo. The measured R_2 values vary between ROIs as predicted, CSF displaying the lowest value and variation with τ_{CP}. The measured volume fraction of the grey matter ROIs are high, however from venogram data we expect there to be a large number of veins in this posterior slice.

Currently the model assumes fast exchange, but in the future we develop an alternative method for comprehensively fitting all the T2 data for blood volume assuming more realistic slow exchange model. This experiment will then be extended to investigate changes in R2 values on activation, with the aim of studying changes in local blood oxygenation and blood volume caused by neuronal activity. We will also optimise the CPMG sequence to allow acquisitions at shorter values of τ_{CP}.

References:

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