Measuring Blood Oxygenation at 2.35T using a Multi-Echo Sequence

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Introduction: The goal of this study is to develop methods of separating the changes in arterial and venous blood volumes, and the change in venous oxygenation, that occur during neuronal activation by using the echo spacing (τ_{cp}) dependence of blood T_2. The apparent T_2 of a voxel in the brain depends on the oxygenation (Y) of its blood, as deoxyhaemoglobin acts as a natural paramagnetic contrast agent. The haematocrit (Hct) determines the volume of the blood occupied by erythrocytes and relates to the total amount of deoxyhaemoglobin in blood. The R_2 is dependent on the τ_{cp} in the measurement sequence[1] because in blood, exchange and/or diffusion occurs between sites of different susceptibility in the erythrocytes and the plasma causing dephasing of the signal. This dephasing can be overcome by the application of a train of 180^0 pulses. Three models have been proposed to explain the echo dependence of blood R_2; those of Luz-Meiboom (LM)[2] and Allerhand[3] [chemical exchange models] and Jensen[4] [diffusion model]. This abstract aims to compare these models for data acquired at 2.35T over a wide range of echo spacings.

Theory: The apparent blood R_2 can be described by the following equations, with the three models calculating the $R_{2,ex}$ component in a different manner.

1a) $R_2 = R_{2,0} + R_{2,ex}$

1b) $R_{2,0} = R_{2,plas} + Hct * [R_{2,ery} - R_{2,plas}]$

1c) $R_{2,ery} = R_{2,plas} + (R_{2,dia} + R_{2,oxy}) + (1 - Y)[R_{2,deoxy} - R_{2,oxy}]$

$R_{2,0}$ is relaxation in the absence of exchange and $R_{2,ex}$ the additional exchange / diffusion contribution. The subscripts plas, dia, oxy and deoxy refer to different blood component R_2 values, for plasma, diamagnetic, oxygenated and deoxygenated haemoglobin[5].

The LM model is known to hold only at small susceptibility shifts ($\Delta\omega$) and breaks down for slow exchange [$\tau.\Delta\omega > 1$] and strongly magnetised particles [$\tau_{cp}.\Delta\omega > 1$]. The Allerhand model is an extension of the LM model, applicable to a wider range of frequency shifts, echo times and field strengths. There is conflict in the values of the exchange time, τ, and $\Delta\omega$ found in the literature, possibly due to the different echo spacings and experimental methods employed. The Jensen model considers diffusion around magnetic perturbers (erythrocytes) in the blood, which cause a susceptibility shift (χ).

2a) $R_{2,ex}^{Luz\text{-}Meiboom} = Hct.(1 - Hct).(\Delta\omega)^2.\tau.\left[1 - \frac{2\tau}{\tau_{cp}}\tanh\left(\frac{\tau_{cp}}{2\tau}\right)\right]$

τ is the exchange time between two sites. τ_{cp} is the echo spacing.

2b) $R_{2,ex}^{Allerhand} = (2\tau)^{-1} - (\tau_{cp})^{-1}\sinh^{-1}F$

F' is a complex function of τ, $\Delta\omega$ and Hct

2c) $R_{2,ex}^{Jensen} = \left(\frac{32}{45}B_0^2 Hct\,(1 - Y)^2\chi^2\right)\frac{\gamma^2 r_c^2}{D} \times \left(\frac{1}{\sqrt{\pi}}\int_0^\infty \frac{e^{-y}}{\sqrt{y}}\left[1 - \frac{r_c^2}{4D\,\tau_{cp}}\tanh\left(\frac{4D\,\tau_{cp}}{r_c^2}y\right)\right]dy\right)$

r_c is a length scale for the spatial variations of field inhomogeneities. D is the diffusion constant.

Method: Blood samples were taken from healthy adult volunteers. Y and Hct were then manipulated by altering plasma content and by gently bubbling either a O_2 or CO_2 (5%) and N (95%) mix through the blood. The sample Y and Hct were measured using an ABL710 Blood Gas Analyser. The samples were then scanned spectroscopically in a 2.35T small-bore magnet (Bruker) at a series of echo spacings, τ_{cp}, from 2 to 60ms in order to obtain their R_2 values. Between one and sixteen 180^0 pulses with four-shot phase cycling were used to acquire the data. The samples were kept at 37^0C and shaken at regular intervals to prevent settling. After scanning each sample Y and Hct were remeasured. The R_2 values were fitted to the models described (eq. 2a-c) for τ, $\Delta\omega$, χ and D/r_c^2. The $R_{2,0}$ parameters were calculated for eq. *1b* and *1c* using fully oxygenated samples (fig 1). It was then possible to fit a wider range of oxygenated samples to the three models using calculated $R_{2,0}$ and eqs. *1a, 2a-c* for 2.35T.

Results: Fig. 1 shows $R_{2,0}$ for fully oxygenated blood samples at different Hct. Fig. 2 shows the model fits for blood R_2 versus τ_{cp}, for different Y values.

Figure 1

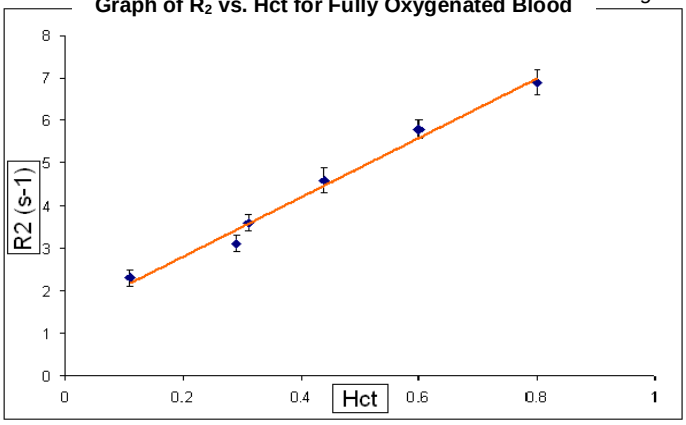
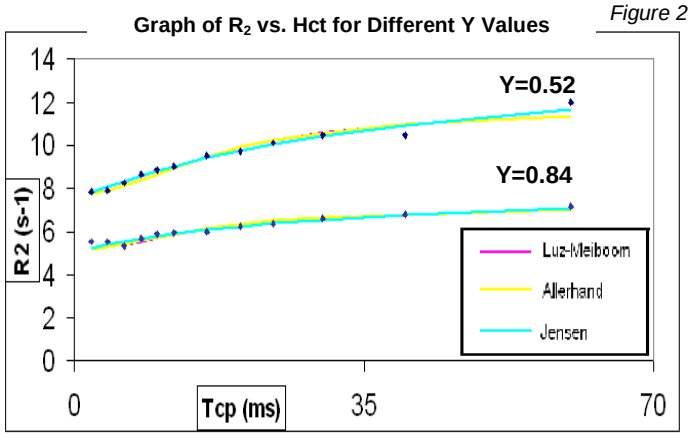


Figure 2



Experimental Parameters				$R_{2,0}$ Parameters			Exchange Parameters		Diffusion Parameters	
Field	**Y**	**Hct**	**τ_{cp} (ms)**	**$R_{2,plas}$ (s^{-1})**	**$R_{2,dia+oxy}$ (s^{-1})**	**$R_{2,deoxy-oxy}$ (s^{-1})**	**τ (ms)**	**$\Delta\omega$ (ppm)**	**χ**	**D/r_c^2 (ms^{-1})**
2.35T	0.5-1	0.1–0.8	2-60	1.5±0.2	6.2±0.4	9.7±0.5	5.0±0.1	-0.18±0.01	6±2 x10^{-8}	60±5

Discussion: Figure 1 shows an excellent fit of data to obtain $R_{2,plas}$ and $R_{2,ery}$. The dependence of blood R_2 on Hct is clearly illustrated, which is consistent with literature results[5,6]. The results in figure 2 show a good fit of the models to the data. The two exchange models showed close agreement whilst the Jensen model gave a better goodness of fit. The R_2 terms found, and the subsequent fitted model parameters, are summarised in the table above. It is likely that a more realistic situation in blood is that of a mix of exchange and diffusion, with restricted diffusion that can then be approximated by exchange. This is the probable cause for the three models giving similar fits. Differences between the model fits are likely to increase at higher field.

References:

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